December 2014

Primary Creep in ASTM A325 Bolts Under Simulated Fire Loading

Mohammad Matar
University of Wisconsin-Milwaukee

PRIMARY CREEP IN ASTM A325 BOLTS UNDER SIMULATED FIRE LOADING

by

Mohammad Matar

A Thesis Submitted in

Partial Fulfillment of the

Requirements for the Degree of

Master of Science

in Engineering

at

The University of Wisconsin-Milwaukee

December 2014

ABSTRACT

PRIMARY CREEP IN ASTM A325 BOLTS UNDER SIMULATED FIRE LOADING

by

Mohammad Matar

The University of Wisconsin-Milwaukee, 2014
Under the Supervision of Professor Adeeb Rahman

At room temperature, small creep effects are present on steel structures. This is not the case at fire condition where the temperature is much higher than room temperature; in this case creep can be significant, and should be taken into consideration. Since fire hazard can happen in any building, creep effect must be taken into consideration when designing a building. Creep strain behaves as a function of time, temperature and stress. As the temperature increases, the creep strain increases. Similarly, the longer the temperature at a given stress on the structure, the more the creep strain present.

The smallest component of steel connection is the steel bolt. Being the smallest component, and most likely highly stressed, it can have significant creep. The ASTM A325 bolt was chosen in this study because it is widely used in steel structures and in the construction industry.

In previous work by Shrih (2013), tensile tests under high temperature on ASTM A325 bolts were performed. A finite element model was developed to simulate his experiments. Temperature-Displacement plots were generated; F.E. results showed good agreement

with the experimental investigations at lower temperatures. At higher temperatures, the F.E. model had shown deviation from experimental results. Creep effects were not considered in the F.E. model in Shrih's work.

In this Thesis it is hypothesized that creep effects are the reason why FE and experimental curves did not match. Further experimental investigations were proposed and performed to account for creep effects. Computational models were developed to predict the creep strain. The models were functions of stress, temperature and time. Since creep was not taken into consideration in the work done by Shrih, the work in this thesis will modify the F.E. result to include the creep effect. The adjusted F.E. results had shown significant agreement compared with the experimental results.

Experimental work that was done during this research to predict creep was simulated using ANSYS software. Finite element results were compared to the experimental results and found to graphically match.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

Chapter 1

Tension bolts in a moment-resisting steel connection are more susceptible to failure during a fire than during service at room temperature. In addition to high temperature (thermal) and load deformation, a third type of deformation comes into play over short periods of time at higher temperatures; creep deformation [21]. Creep normally happens over long periods of time. This is not the case for steel bolts placed under high temperatures, where creep deformation happens relatively quickly. The increased speed of creep at higher temperatures means that creep becomes an important factor that could lead to failure and should be taken into consideration when designing steel connections. [3]

1.1 Organization of the Manuscript

This thesis was divided into four chapters. The first chapter discusses the problem statement, the objectives of research, literature review of creep definition and details, creep models, ASTM A325 bolt. The second chapter discusses the experimental work, data analysis, developing computational models, and using the models to solve a problem. The third chapter discusses the development of F.E. modelling of the experiments performed for this research, and comparison between the F.E. results and the experimental results. The fourth chapter discusses a summary of the completed work, conclusions, suggestions, limitations, and suggested future work.

1.2 Problem Statement

Any building or structure is susceptible to catch fire. The probability of catching fire varies depending on the use of the building. Design codes make reference and design recommendations for fire loadings. Thermal expansion and creep are important factors that should be taken into consideration when designing bolts used in steel connections.

This research experimentally examines the effect of creep under elevated temperatures in tensile loading on structural A325 steel bolt. Finite element analyses were also used to predict the behavior of the same bolt under similar conditions in order to validate the experimental results. ANSYS Workbench was used to perform the F.E. analysis.

In this research, four computational models were developed to predict the creep strain (ε_{cr}). The models were functions of stress, temperature and time. Models for loading under constant temperatures 450^{o}C, 500^{o}C and 550^{o}C were developed as well as a general model that accounts for variable temperature.

In previous work by Shrih (2013) [1], ASTM A325 bolts were tested under constant tensile force and variable temperature. Finite Element simulation of the experimental work was done. A temperature vs. Displacement plot was generated as shown in Figure 1.1. It is clear that the F.E curve diverges from the experimental curves around a temperature of 500^{o}C. This means that the displacements predicted by this model for the sample at temperatures higher than 500^{o}C is less than experimental displacement for the same sample. By examining the research and F.E. analysis that was done in Shrih's work, it was found that creep was not taken into consideration in the F.E. simulation model.

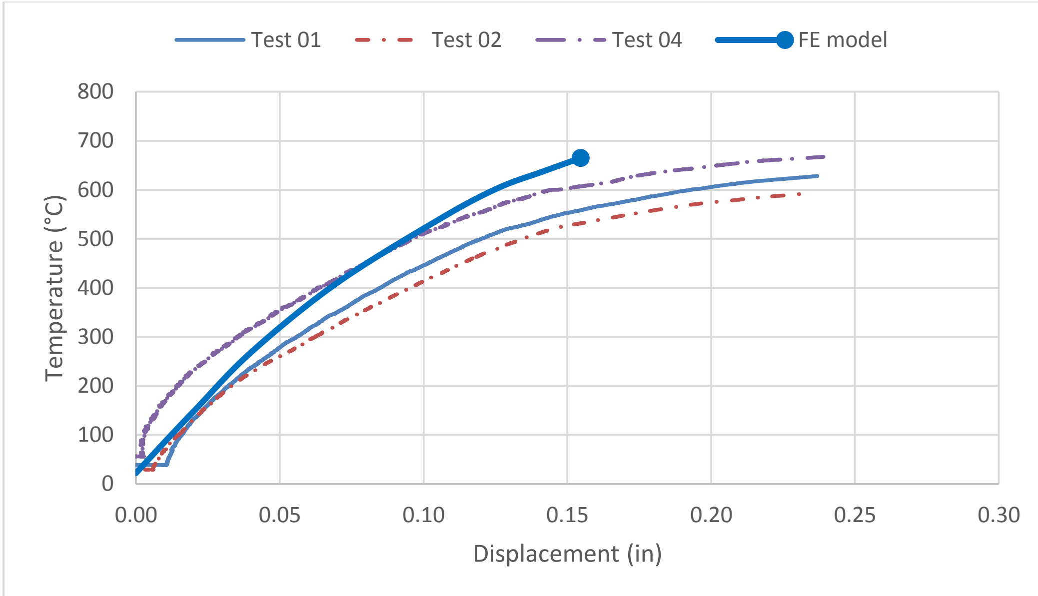


Figure 1.1 Temperatures- Displacement Comparison of experiments and F.E. in the research done by Shrih (2013) [1]

Since creep was not taken into consideration in the work done by Shrih (2013), the models developed in this research will be used to adjust the F.E. curve by adding creep effect. Modified Time-Hardening model was adopted to generate all computational models.

1.3 Research Objectives and Scope

In this research, the following objectives are considered:

1. To conduct tensile tests under elevated temperatures of A325 bolts and record deformation data to study and analyze the effect of creep.
2. To develop an individual creep model for each of temperatures used in the experiments (450°C, 500°C and 550°C) under a constant load of 2000 lb using regression analysis.

3. Develop a general creep models that will work at any temperature between 450°C and 550°C under a constant load of 2000 lb using regression analysis.
4. To apply the models developed in this research to adjust a previous finite element analysis work by adding the effect of creep.
5. Create a finite element model to simulate the conducted experiments and compare the experimental results to the F.E. simulated results.

1.4 Definition of creep

Creep of materials is defined as time-dependent plastic strain that contributes to the loss of strength of steel under elevated temperatures. Creep in metals starts to be significant at a temperature around one-third of its melting point which is around 1400°C for steel; however, the melting temperature varies depending on the steel alloy used. This means that creep is expected to significant at temperatures above 450°C. [2, 3,19]

Creep behavior of steel is an important factor that should be taken into consideration in design of steel connections. A bolt is one of the main components of a moment-resisting connection. Having a proper design of all the other components does not ensure bolts will hold the system together. The survival of the entire connection system during a fire can depend on the safety of those bolts.

1.5 Stages of creep

Creep is the continued deformation of a material under the effect of time, load, and temperature. Creep passes through three distinct stages as illustrated by Figure 1.1 [4] where the creep strain is plotted versus time at constant temperature and stress. Creep strain rate changes instantaneously with change in time. Strain rate behavior can be divided into three phases; the different creep stages [20].

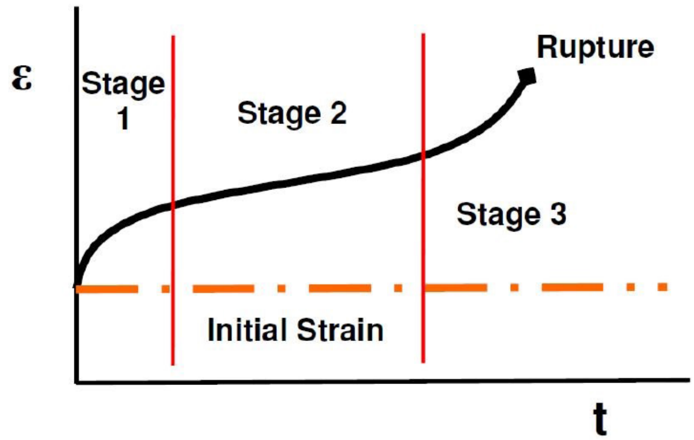


Figure 1.2 Creep strain vs time at constant temperature and stress [4]

The slope of the curve in Figure 1.1 is called the "creep strain rate". Creep strain rate defines the three stages of the creep phenomena. Creep occurring at the first stage starts with high creep rate that slows down with time, this stage of creep is called "**primary creep**". As is clearly visible in Figure 1.1, the creep rate in the second stage is lower than the first stage. This second stage is called "**secondary creep**", this stage lasts longer than the primary creep and the creep rate is much smaller than the rate in the other stages. Creep rate during the secondary creep stage is relatively uniform. After the second stage, the third stage of creep starts where the creep rate starts to accelerate until failure of the material. This stage is called "**tertiary creep**". [3, 6, 20].

1.6 Types of Creep Strain

A review of literature shows a lack of research about the effect of creep on steel behavior at fire condition. Various types of steel are available and each type shows different creep behavior; this was studied in different papers [7, 8]. Harmathy has developed a model to predict primary and secondary creep, this model is applicable at steadily increasing temperatures and slowly varying load, this model was a function of stress (load), temperature, and time [8]. Another work by Harmathy and Stanzak shows that this model worked fairly well at two types of structural steels and a prestessing steel [9].

There are two cases of creep strain. The first case is when the stress is constant and close to steady state; this case is called time hardening. In time hardening, creep strain rate ($\dot{\varepsilon}_{cr}$) is a function of time (t) and stress (σ) as shown in Equation 2.1. The second case is when the stress is changing with time; this case is called strain hardening. In strain hardening case, creep strain rate ($\dot{\varepsilon}_{cr}$) is a function of creep strain (ε_{cr}) and stress (σ) as shown in Equation 2.2. The equations assume that there is no change in the temperature. When there is a change in the temperature, (T) should be included in both equations. [10, 11, 12]

$\varepsilon_{cr} = \int_0^t \dot{\varepsilon_{cr}}(t,\sigma)dt$ …….. Eq. 2.1

$\varepsilon_{cr} = \int_0^t \dot{\varepsilon_{cr}}\,(\varepsilon_{cr},\sigma)dt$ …….. Eq. 2.2

1.7 Creep Models

Modified time-hardening creep model was used in this research to model and analyze results and proved a good fit for the data and experimental results. Modified time-hardening creep model is a standard model in ANSYS, this model was used in this research and it is basically the integral of the time-hardening creep model. It is one of the 13 creep models that ANSYS provides. Modified time-hardening creep model was selected as it represents the primary creep which is the main interest in this research. A complete list of models available in ANSYS is presented in Table 1-1.

Table 1-1: Creep models used in ANSYS [13]

Creep Model	Name	Equation	Type
1	Strain Hardening	$\dot{\varepsilon_{cr}} = C1\, \sigma^{C2} {\varepsilon_{cr}}^{C3} e^{-C4/T}$	Primary
2	Time Hardening	$\dot{\varepsilon_{cr}} = C1\, \sigma^{C2} t^{C3} e^{-C4/T}$	Primary
3	Generalized Exponential	$\dot{\varepsilon_{cr}} = C1\, \sigma^{C2} r e^{-rt}$ $r = C5\, \sigma^{C3} e^{-C4/T}$	Primary
4	Generalized Graham	$\dot{\varepsilon_{cr}} = C1\, \sigma^{C2} (t^{C3} + C4 t^{C5} + C6 t^{C7}) e^{-C8/T}$	Primary
5	Generalized Blackburn	$\dot{\varepsilon_{cr}} = f(1 - e^{-rt}) + gt$ $f = C1\, e^{C2\, \sigma}$ $r = C3(\sigma/C4)^{C5}$ $g = C6\, e^{C7\, \sigma}$	Primary
6	Modified Time Hardening	$\varepsilon_{cr} = C1\, \sigma^{C2}\, t^{C3+1}\, e^{-C4/T}/(C3+1)$	Primary
7	Modified Strain Hardening	$\dot{\varepsilon_{cr}} = \{C1\, \sigma^{C2}\, [(C3+1)\varepsilon_{cr}\,]^{C3}\}^{1/(C3+1)}\, e^{-C4/T}$	Primary
8	Generalized Garofalo	$\dot{\varepsilon_{cr}} = C1[\sinh(C2\, \sigma)]^{C3} e^{-C4/T}$	Secondary
9	Exponential form	$\dot{\varepsilon_{cr}} = C1\, e^{\sigma/C2}\, e^{-C3/T}$	Secondary
10	Norton	$\dot{\varepsilon_{cr}} = C1\, \sigma^{C2}\, e^{-C3/T}$	Secondary
11	Combined Time Hardening	$\varepsilon_{cr} = \dfrac{C1 \sigma^{C2}\, t^{C3+1} e^{-C4/T}}{C3+1} + C5\, \sigma^{C6} t\, e^{-C7/T}$	Primary + Secondary

12	Rational Polynomial	$\dot{\varepsilon_{cr}} = C1 \frac{d\varepsilon_c}{dt}, \varepsilon_c = \frac{cpt}{1+pt} + \dot{\varepsilon_m} t , \dot{\varepsilon_m} = C2\, 10^{C3\,\sigma}\, \sigma^{C4}$ $c = C7(\dot{\varepsilon_m})^{C8}\, \sigma^{C9}, p = C10\, (\dot{\varepsilon_m})^{C11} \sigma^{C12}$	Primary + Secondary
13	Generalized Time Hardening	$\varepsilon_{cr} = f\, t^r\, e^{-C6/T}$ $f = C1\,\sigma + C2\,\sigma^2 + C3\,\sigma^3$ $r = C4 + C5\,\sigma$	Primary

Where,

ε_{cr} = equivalent creep strain

$\dot{\varepsilon}_{cr}$ = change in equivalent creep strain with respect to time (creep strain rate)

σ= equivalent stress

T= temperature (absolute)

C1 through C12 = Constants

t= time

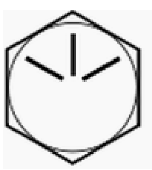
e= natural logarithm base

1.8 ASTM A325 Bolt

1.8.1 ASTM A325 Bolt Types and Mechanical Properties

ASTM A325 is an ASTM International standard for heavy hex structural bolt. Table 1-2 shows the head markings and mechanical properties for imperial sizes of ASTM A325 bolt.

Table 1-2: Head markings and mechanical properties for ASTM A325 bolt [14]

<table>
<tr><th rowspan="2">Identification Grade Mark</th><th rowspan="2">Specification</th><th rowspan="2">Fastener Description</th><th rowspan="2">Material</th><th rowspan="2">Nominal Size Range (in.)</th><th colspan="2">Mechanical Properties</th></tr>
<tr><th>Yield Strength Min (psi)</th><th>Tensile Strength Min (psi)</th></tr>
<tr><td rowspan="2">
or
</td><td rowspan="2">ASTM A325
Type 1</td><td rowspan="5">High Strength Structural Bolts</td><td rowspan="2">Medium Carbon Steel, Quenched and tempered</td><td>1⁄2–1</td><td>92</td><td>120</td></tr>
<tr><td>1–1-1⁄2</td><td>81</td><td>105</td></tr>
<tr><td></td><td>ASTM A325
Type 2</td><td>Low Carbon Martensitic Steel, Quenched and Tempered</td><td>1⁄2–1</td><td>92</td><td>120</td></tr>
<tr><td rowspan="2"></td><td rowspan="2">ASTM A325
Type 3</td><td rowspan="2">Atmospheric Corrosion Resisting Steel, Quenched and Tempered</td><td>1⁄2–1</td><td>92</td><td>120</td></tr>
<tr><td>1–1-1⁄2</td><td>81</td><td>105</td></tr>
</table>

1.8.2 ASTM A325 Bolt Stress-Strain Diagram

Tensile testing at room temperature was performed during the study for a standard ASTM A325 bolt to make sure the tensile strength at least matches or exceeds the standard minimum tensile strength. Figure 1.3 shows the Stress-Strain curve. A value of 31290 ksi for modulus of elasticity (*E*) was calculated from the diagram which is close to the standard values of 29,000 ksi for this kind of bolt.

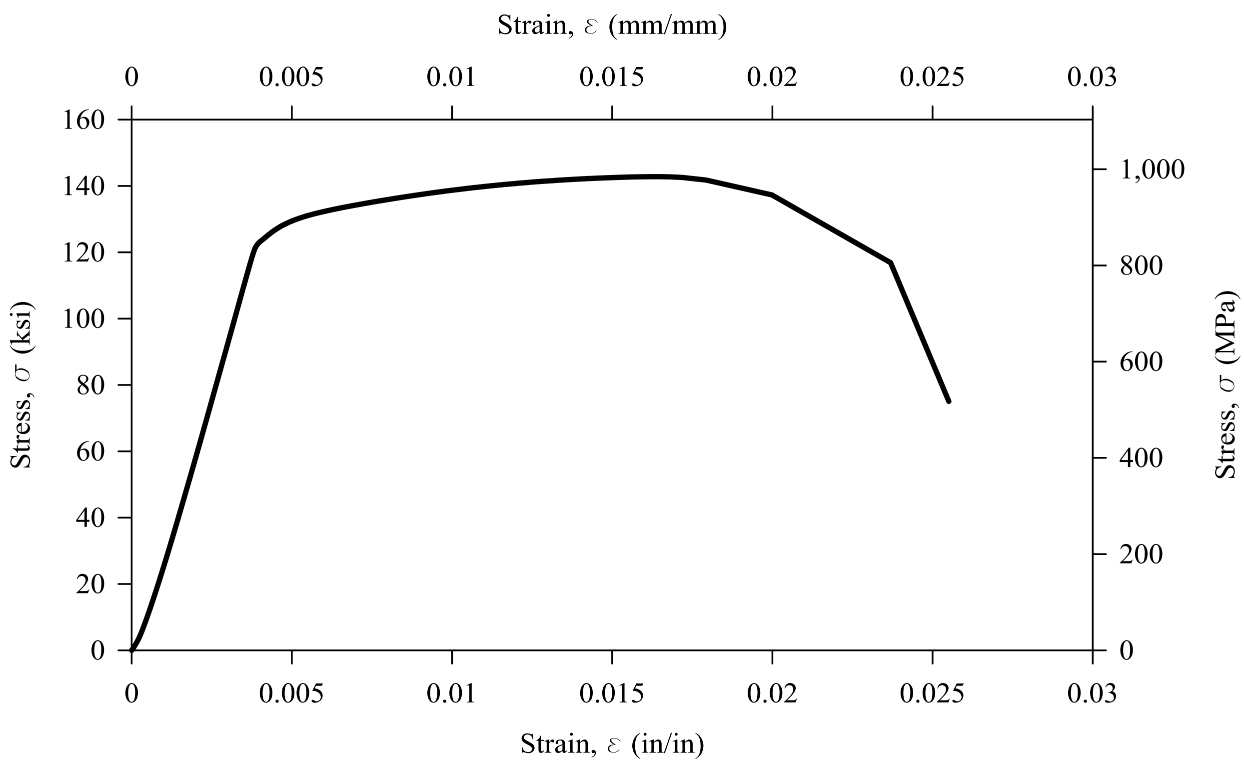


Figure 1.3: Stress-Strain Curve of ASTM A325 Bolt

1.8.3 ASTM A325 Bolt Dimensions

Available dimensions of ASTM A325 bolts are shown in Table 1-3. Where,

D: diameter of the bolt

L.T.: length of the threaded part of the bolt

Dimensions F, G, h and B are shown in Figure 1.4

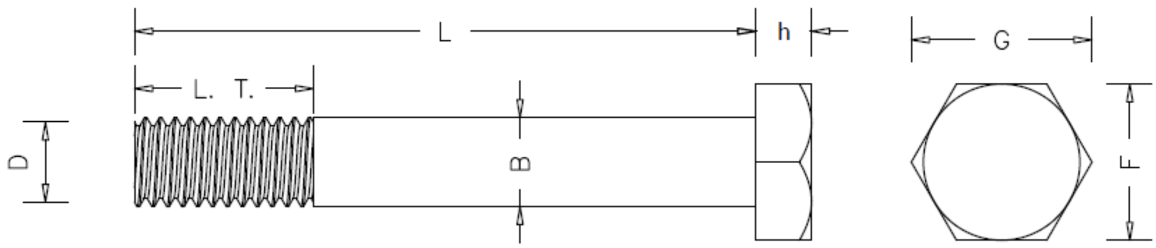


Figure 1.4: ASTM A325 Bolt Dimensions [1]

Table 1-3: Dimensions of available A325 bolts (ASME B18.2.6 2003)

D	F Max.	G Max	B Max.	H Nom.	LT	Length Range
½”	0.875”	1.010”	0.515”	5/16”	1.00”	1-1/2” -4”
5/8”	1.062”	1.227”	0.642”	25/64”	1.25”	1-1/2” -8”
¾”	1.25”	1.443”	0.768”	15/32”	1.38”	½” -8”
7/8”	1.438”	1.660”	0.895”	35/64”	1.5”	1-1/2” -8”
1”	1.625”	1.876”	1.022”	39/64”	1.75”	1-1/2” -8”
1-1/8”	1.812”	2.093”	1.149”	11/16”	2.00”	2” -8”
1-1/4”	2.000”	2.309”	1.276”	25/32”	2.00”	2” -8”
1-3/8”	2.188”	2.526”	1.404”	27/32”	2.25”	2-1/2” -8”
1-1/2”	2.375”	2.742”	1.522”	15/16”	2.25”	2-1/2” -8”

1.8.4 Material Properties of the Sample and Setup Component

ASTM A325 bolts are commonly used in the United States as structural fasteners. During a fire, the performance of these bolts will be adversely affected by the loss of strength due to higher temperatures resulting in increased susceptibility to creep deformations

[15]. The European code [5] provides reduction factors for the stress-strain relationship of steel at elevated temperatures, but these factors do not consider the effects of time-dependent deformations on heated steel. Steel bolts, rods, and steel channel sections used in all experiments have the properties shown in Table 1-4 at room temperature. Table 1-5 shows material properties at various temperatures, these properties were used in the finite element model to account for the loss of strength that is resulting from increasing temperature.

Table 1-4: Material properties of bolts, rods, and steel sections at room temperature [15]

Property	Value	Unit
Young's Modulus (E)	29000	ksi
Poisson's Ratio	0.3	-
Density	490	lb/ft^3
Thermal Expansion	$1.2x10^{-5}$	1/°C
Thermal Conductivity	60.5	W/m.°C
Specific Heat	434	J/kg.°C

Table 1-5: Material properties of bolts, rods, and steel sections at various temperatures [1]

Temperature F	Young's Modulus psi	Poisson's Ratio	Bulk Modulus psi	Shear Modulus psi
71.6	2.9e+006	0.3	2.42e+007	1.12e+007
212	2.9e+006	0.3	2.42e+007	1.12e+007
392	2.61e+007	0.3	2.18e+007	1.00e+007
572	2.32e+007	0.3	1.93e+007	8.92e+006
752	2.03e+007	0.3	1.69e+007	7.81e+006
932	1.74e+007	0.3	1.45e+007	6.69e+006
1112	8.99e+006	0.3	7.49e+006	3.46e+006
1292	3.77e+006	0.3	3.14e+006	1.45e+006
1472	2.61e+006	0.3	2.18e+006	1.00e+006
1652	1.96e+006	0.3	1.63e+006	7.54e+005

1.9 Temperatures Used in the Experimental Work

The temperatures used in conducting the experiments in this research were 450°C, 500°C, and 550°C. The temperatures chosen for this research are indicative of the temperatures of structural members during a standard fire. Although the flames of a fire may have a higher temperature range than its surroundings, structural steel members are likely to collapse long before they reach 900°C. The range of 450°C - 550°C was chosen because it is when large deformations start to develop in steel members. The range of temperature studied in this paper [450°C- 550°C] is a good representation of creep process in steel. Temperature of 450°C was selected as the lower limit of the range because creep is not evident at temperatures below 450°C; creep in metals starts to be significant at a temperature of around one-third of its melting point which for steel is around 1400°C [2]. This was found experimentally by performing a test at 400°C. The result of that test did not show significant creep deformations over a time of two hours. Temperature of 550°C was selected as the higher limit because creep will happen faster at higher temperatures, this will lead to a less stable experiment. This was observed as parts of the setup fixtures of the experiment started to fail or deform at 600°C. This means that calculated creep deformation values will not represent the sample bolt only, it will represent both the bolt and the setup fixtures, which is not what the goal of experiment is. At the range of [450°C - 550°C] the creep deformation in the setup fixtures (not the bolt) can be ignored, this means more accurate creep deformation data of the bolts tested.

Chapter 2

2.1 Setup of Experiments

The tested specimens consisted of a 0.5-inch ASTM A325 bolt, two hollow structural steel sections and two bars. A custom-built electric furnace with controlling unit was used to heat the specimen to the required temperature. The furnace was fitted into a steel frame as shown in Figure 2.1. Figure 2.2 shows the assembled experiment setup used in all experiments. The picture to the right shows the actual setup with the furnace open.

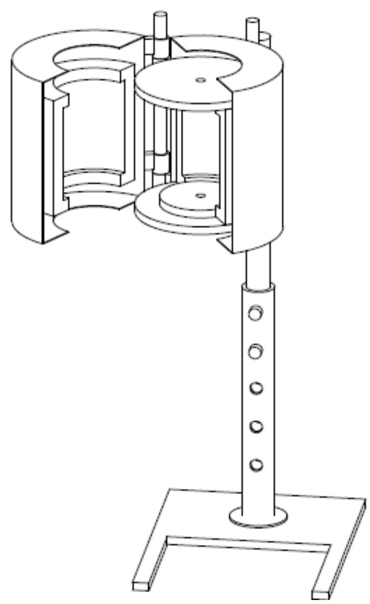


Figure 2.1 Electric Furnace and Frame [1]

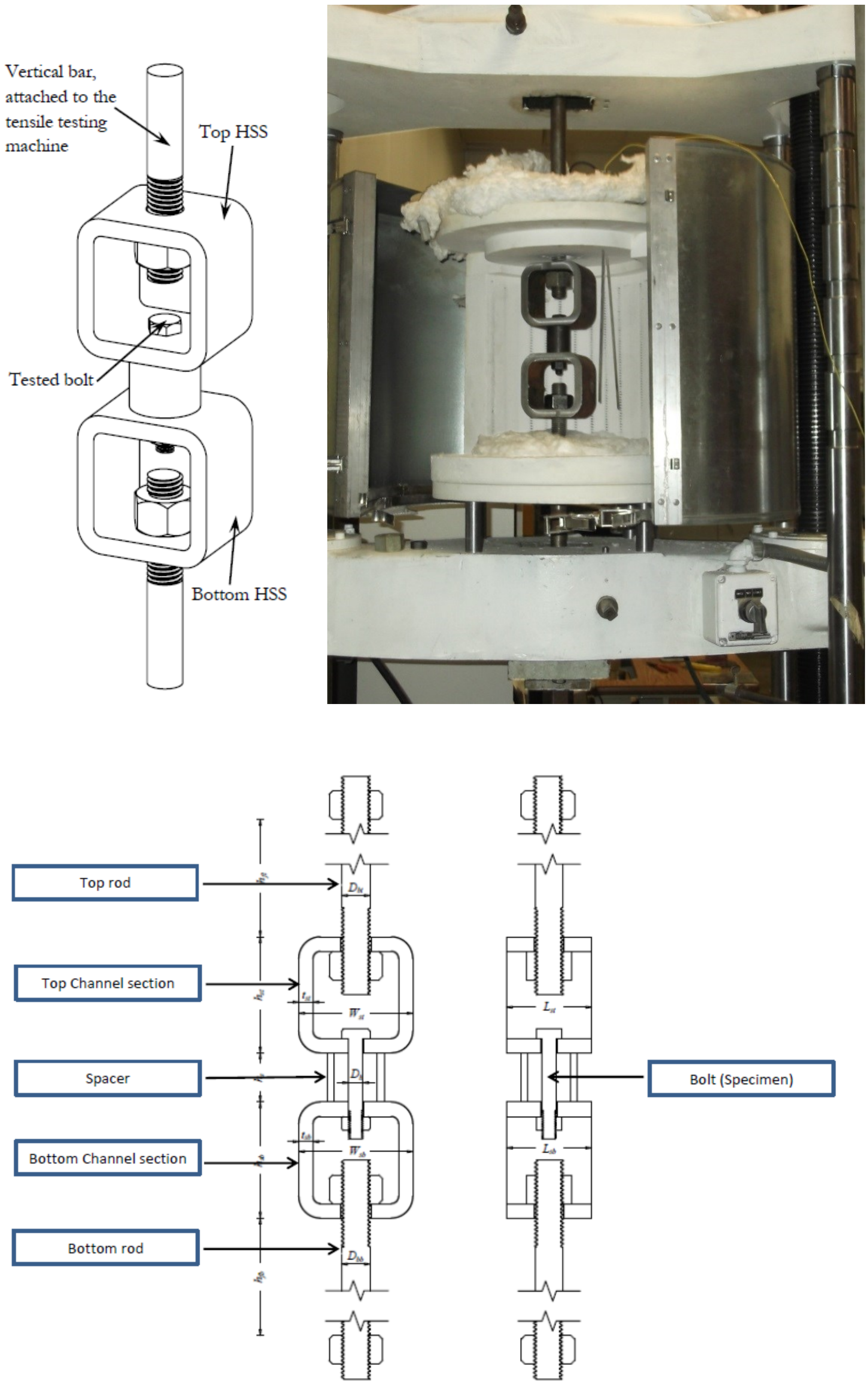


Figure 2.2 Experiment Setup [1] and a picture of one of the bolts tested

2.2 Experimental sets

Three sets of experiments were performed, with a total of seven experiments. Constant load was applied on all experiments and different temperatures were applied on each set.

Table 2.1 shows the sets of experiments performed and details of each set.

Table 2.1. Experiments and Corresponding Load and Temperature

Experiment Set	Load (lb)	Temperature (^{o}C)	Number of Experiments
1	2000	450	3
2	2000	500	2
3	2000	550	3

Set 1: Three experiments were performed in this set; a constant 2000-lb load and constant temperature of $450^{o}C$ were applied during all experiments. Figures 2.3 and 2.4 show the rates of heating and loading for this set. The first experiment in this set was done for the purpose of exploration. The data of the remaining two experiments were used.

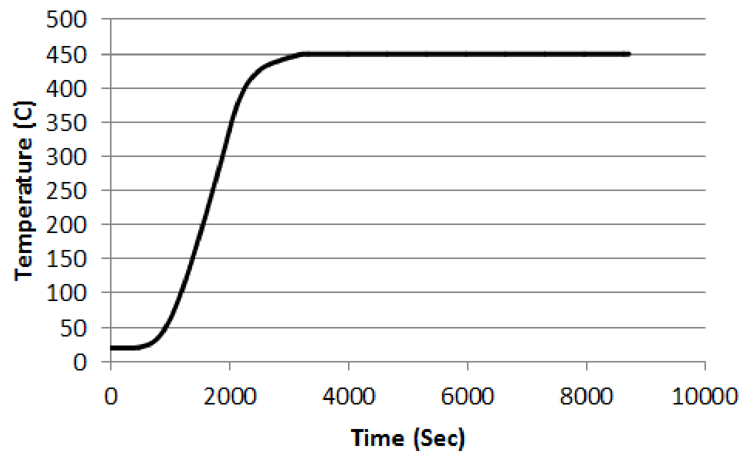


Figure 2.3 Rate of Heating for the First Set of Experiments

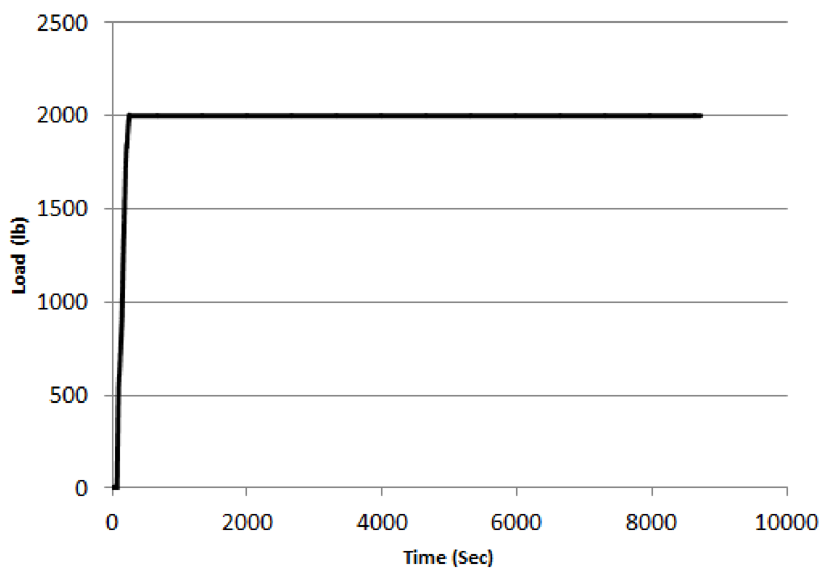


Figure 2.4 Rate of Loading for the First Set of Experiments

Set 2: Two experiments were performed in this set; a constant 2000-lb load and constant temperature of 500^{o}C were applied during both experiments. Figures 2.5 and 2.6 show the rates of heating and loading for this set.

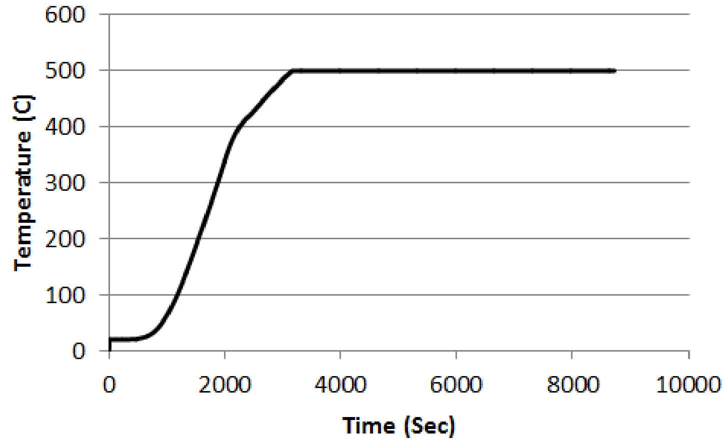


Figure 2.5 Rate of Heating for the Second Set of Experiments

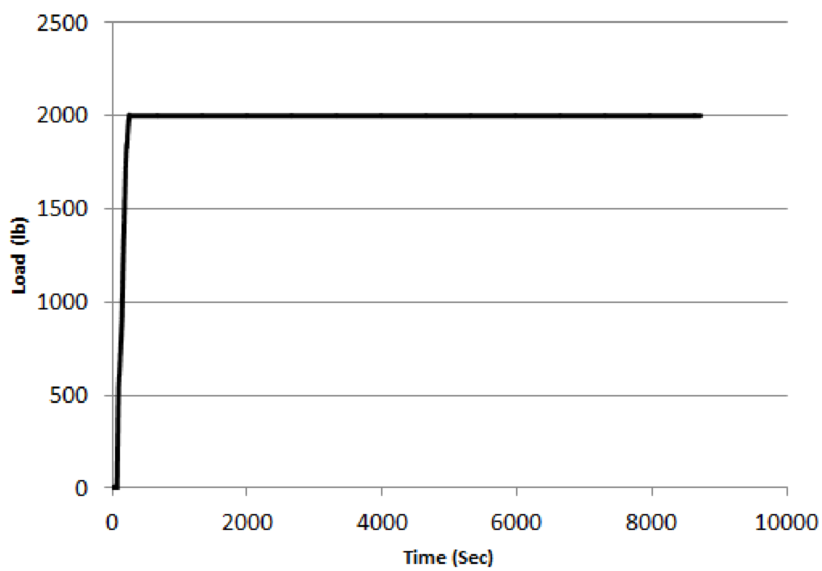


Figure 2.6 Rate of Loading for the Second Set of Experiments

Set 3: Three experiments were performed in this set; a constant 2000-lb load and constant temperature of 550^{o}C were applied during all experiments. Figures 2.7 and 2.8 show the rates of heating and loading for this set. The data of two of these experiments were used; one experiment was done for the purpose of exploration and verification.

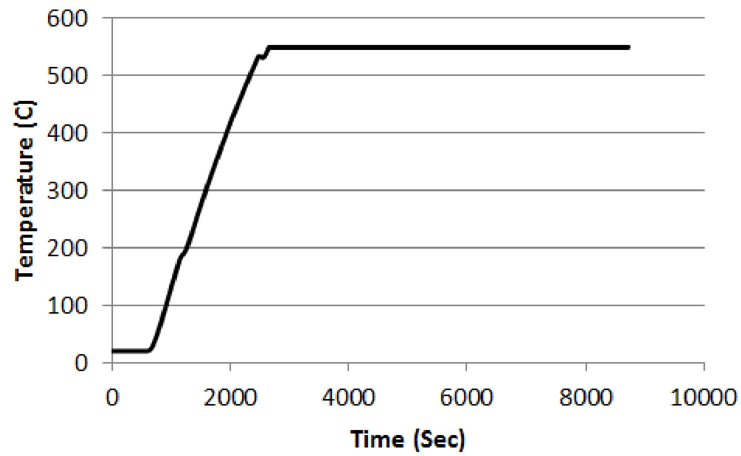


Figure 2.7 Rate of Heating for the Third Set of Experiments

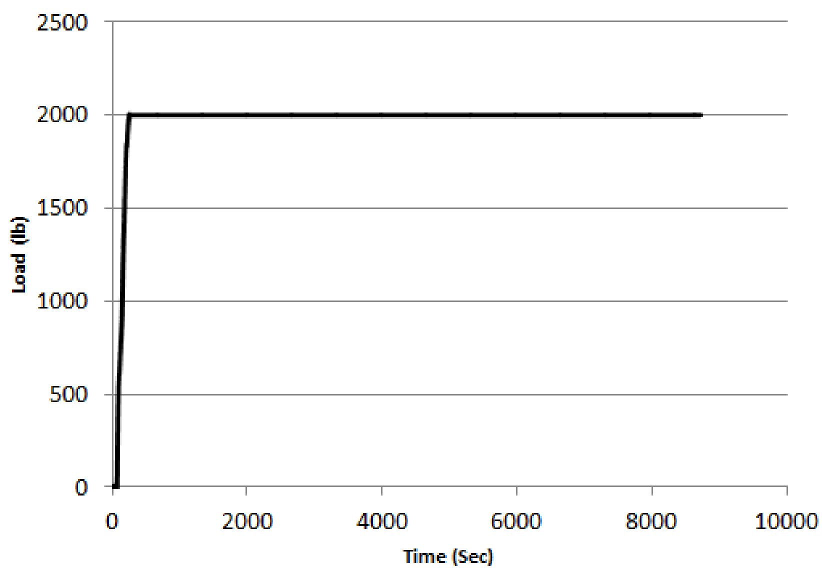


Figure 2.8 Rate of Loading for the Third Set of Experiments

2.3 Load and Temperature Control and Data Acquisition

Load Measurement and Control:

Load was measured directly from the load cell connected to the computer software. The software records the load every second during the experiment. Load was controlled manually using the load handles shown in Figure 2.9. This caused the load to be applied in cycles as shown in Figure 2.10. This will be an important factor in explaining the developed creep strain models as they were generated using the experimental (actual) data, not the fitted data. In other words, the load in Figure 2.10 was used to generate the creep strain models, not those in Figure 2.8.

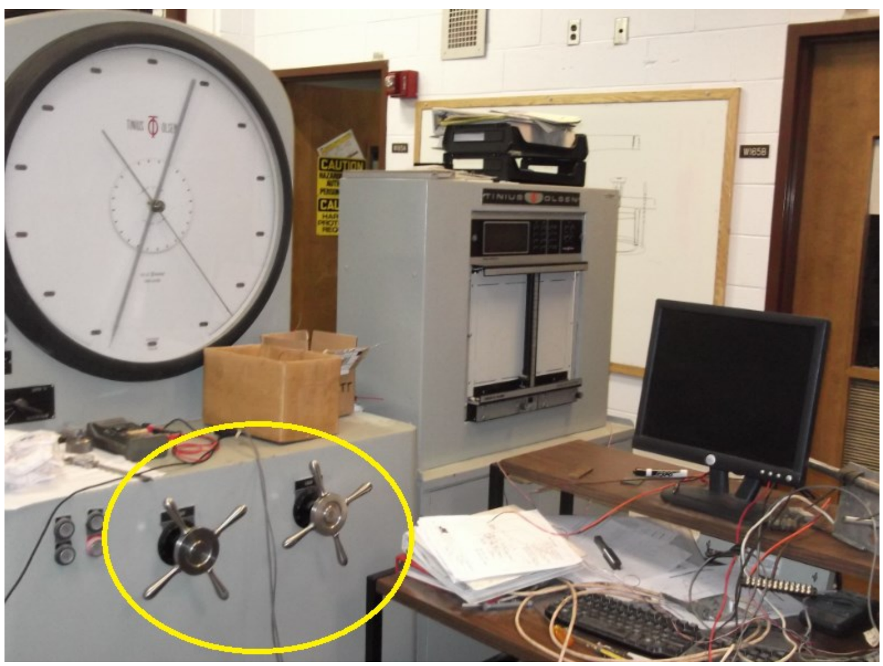


Figure 2.9 Loading Machine (handles are circled)

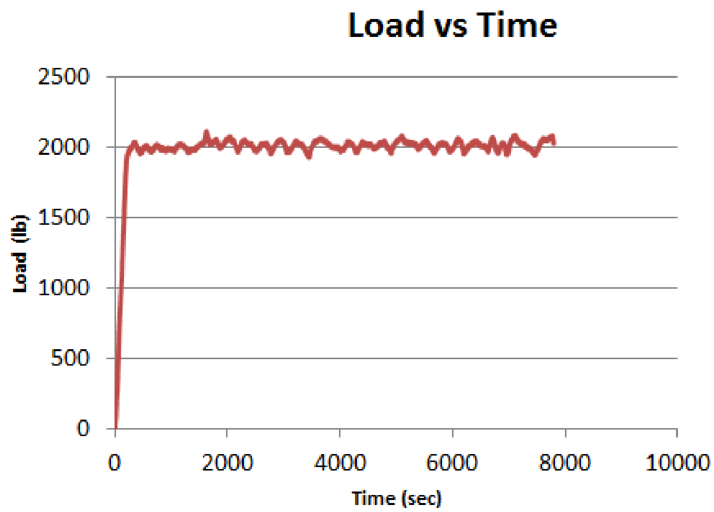


Figure 2.10 Experimental (Actual) Rate of Loading for the Experiments

2.4 Temperature Measurement and Control

Temperature in the furnace was measured using two type-K thermocouples. In some experiments one extra thermocouple was used for verification. All thermocouples in the furnace were installed to stay in contact with the upper steel channel, so that it will read the temperature of the bolt as shown in Figure 2.11. One thermocouple was connected to the furnace controlling unit; the other one was connected to the data acquisition computer software to be recorded. Data acquisition software recorded temperature, every second.

Figure 2.11 Experiment Setup with Thermocouples

Fitted Temperature with respect to time curves were shown previously in Figures 2.3, 2.5 and 2.7. Actual temperatures were applied in cycles. The controlling unit was not able to keep a constant temperature in most experiments; temperature was kept in a range of ±10~20 around the desired temperature. This will also be another important factor in explaining the developed creep strain models as they were generated using the experimental (actual) data, not the fitted data. In other words, the temperatures in Figure 2.12 were used to generate the creep strain models, not those in Figure 2.13.

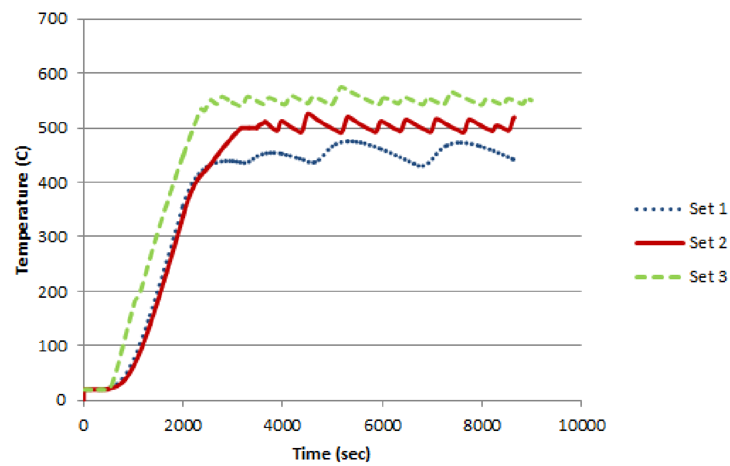


Figure 2.12 Experimental (Actual) Rate of Heating for the Experiments

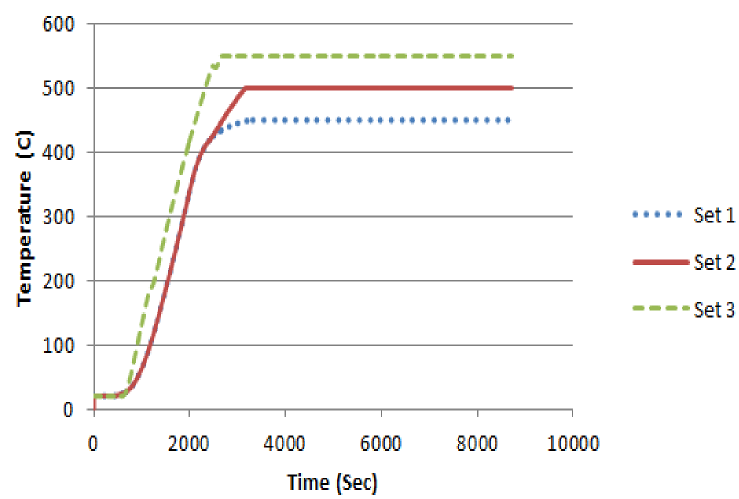


Figure 2.13 Fitted Rate of Heating for the Experiments

2.5 Deformation Measurement

Displacement that occurs in the specimen was measured using a linear variable differential transformer module (LVDT). The LVDT was calibrated before every experiment using an object with known thickness. All deformation and temperature readings are transferred to the computer system and saved to be processed later.

2.6 Experiments results

The data resulted from the experiments were plotted as follows:

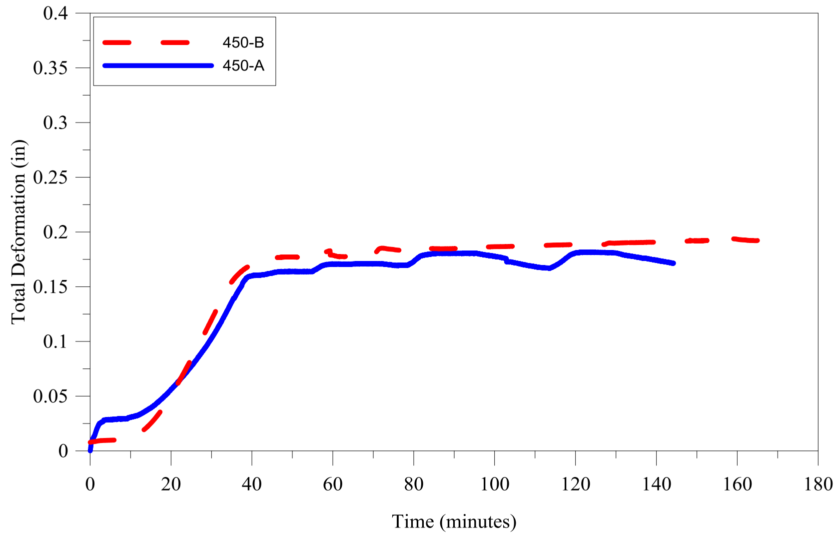


Figure 2.14: Experimental Results of the First Set (T=450^{o}C)

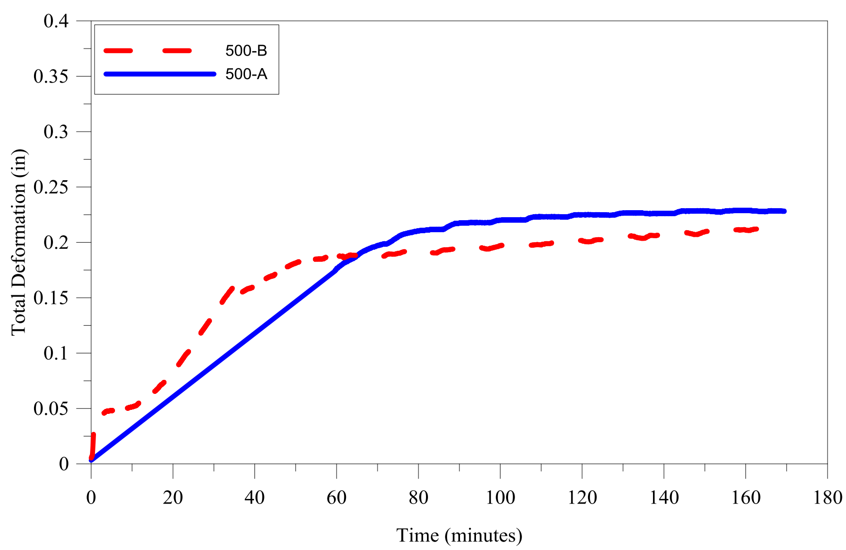


Figure 2.15: Experimental Results of the Second Set (T=500^{o}C)

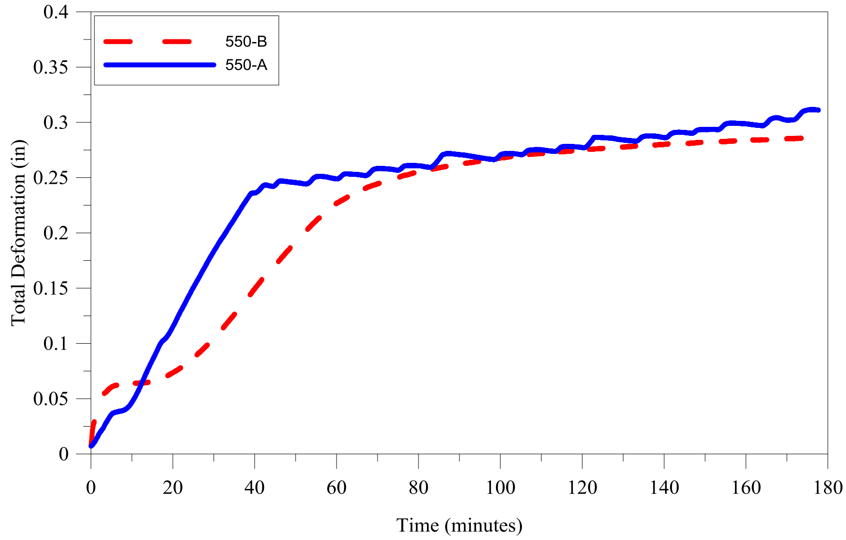


Figure 2.16: Experimental Results of the Third Set (T=550°C)

Figures 2.14, 2.15 and 2.16 show the deformation of each experiment with respect to time. Curves of each set of experiments are close. Data from all experiments are shown in Figure 2.17. The figure shows it can be seen that the higher the temperature the higher the deformation; which is what was expected before performing the experiments. The average of experiments of each set is plotted. Figure 2.18 shows the smoothened curve of the average experimental results.

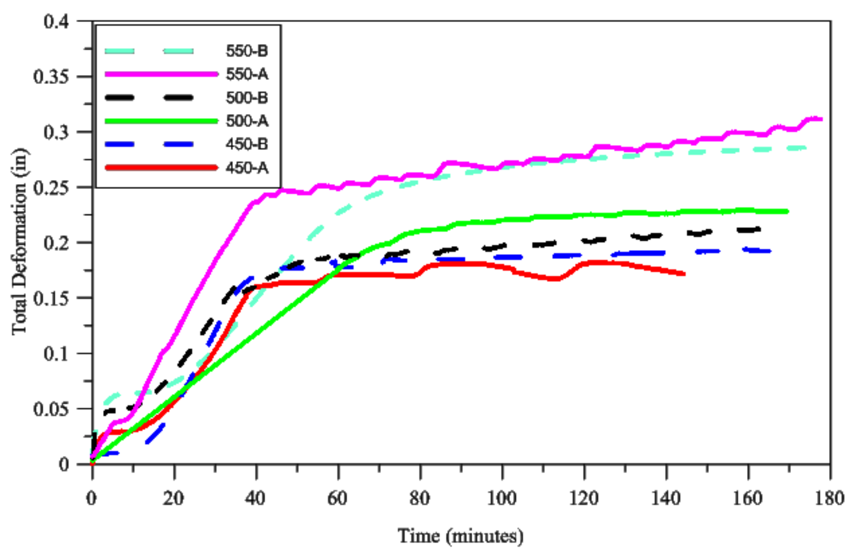


Figure 2.17: Experimental Results of All Experiments

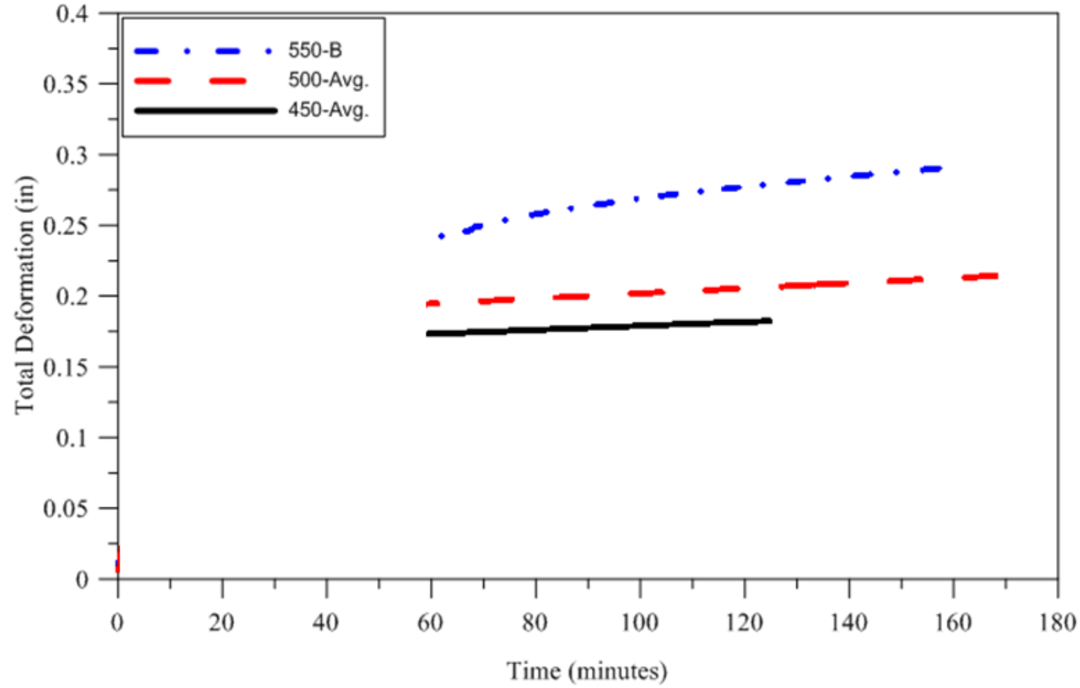


Figure 2.18: Average Experimental Results of All Sets of Experiments

2.7 Analysis of results

The curves show that after about 50 minutes, the deformation curve starts to increase with a small rate. Since load and temperature were both constants, the only mechanism that induces further deformation with time is creep. Deformations due to mechanical load and thermal expansion for the whole setup are manually calculated. Deformation due to creep is calculated by subtracting the thermal expansion and the mechanical load deformation from the total deformation as shown in Equation 2.4. Most of steel rods length is outside the furnace, and their cross section is relatively large. Therefore, they are expected to not experience creep. The steel sections are assumed to have negligible creep deformation due to their size and cross section. Creep deformation is assumed to happen in the bolt only, being the weaker component.

$$\varepsilon_{\text{total}} = \varepsilon_{\text{load}} + \varepsilon_{\text{temperature}} + \varepsilon_{\text{creep}} \qquad \text{eq. (2.1)}$$

$$\varepsilon_{\text{total}} = \frac{P}{AE} + \alpha\,\Delta T + \varepsilon_{\text{creep}} \qquad \text{eq. (2.2)}$$

$$\delta_{\text{total}} = \frac{PL}{AE} + \alpha\,\Delta T\,L + \delta_{\text{creep}} \qquad \text{eq. (2.3)}$$

$$\delta_{\text{creep}} = \delta_{\text{total}} - \frac{PL}{AE} - \alpha\,\Delta T\,L \qquad \text{eq. (2.4)}$$

where,

ε_{total}: Total experimental strain

ε_{load}: Strain due to mechanical load

$\varepsilon_{temperature}$: Strain due to thermal expansion

ε_{creep}: Strain due to creep

P: Tensile load

A: Cross-sectional area

L: Length of component

ΔT: Change in temperature

α: Coefficient of thermal expansion

δ_{total}: Total experimental deformation

δ_{creep}: Deformation due to creep

E: Modulus of elasticity

Deformation due to creep was calculated using Equation 2.4 by subtracting the thermal expansion and the mechanical load deformation from the total deformation. Figures 2.19, 2.20 and 2.21 show the total experimental deformation curves for each set and the corresponding creep deformation curve calculated using Eq. 2.4.

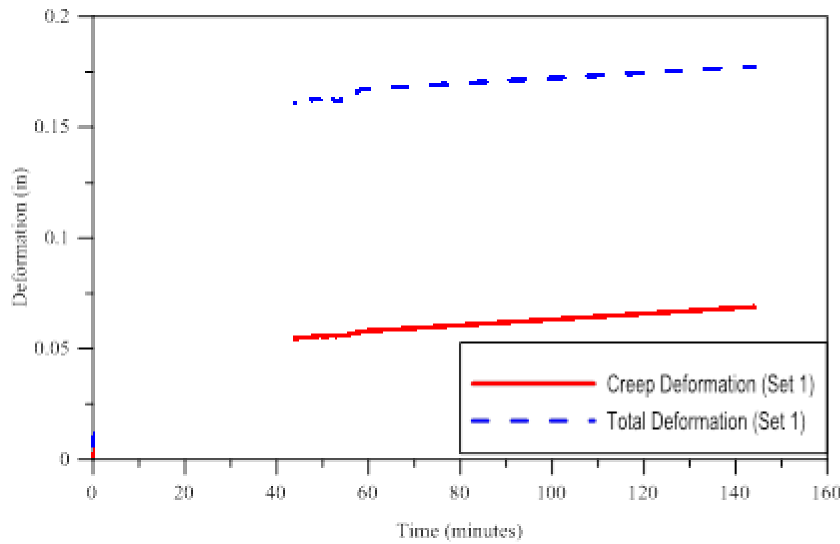


Figure 2.19: Total Deformation and Creep Deformation Curves for Set 1

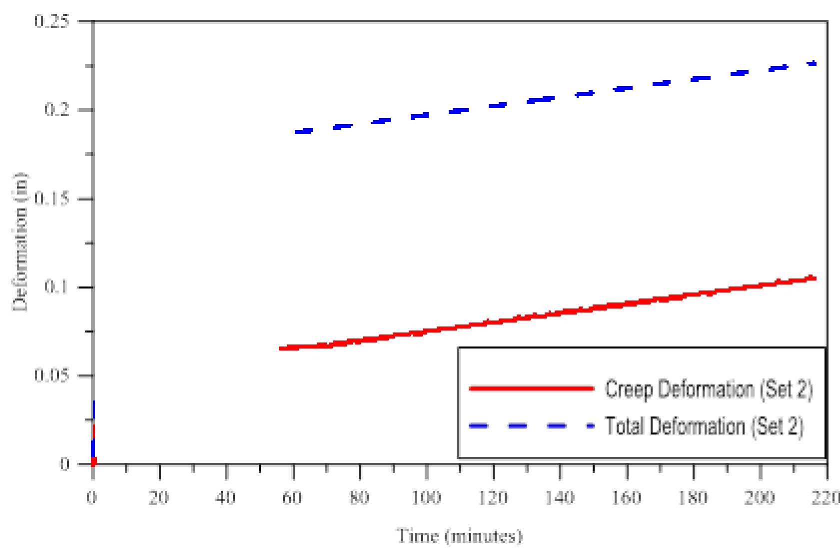


Figure 2.20: Total Deformation and Creep Deformation Curves for Set 2

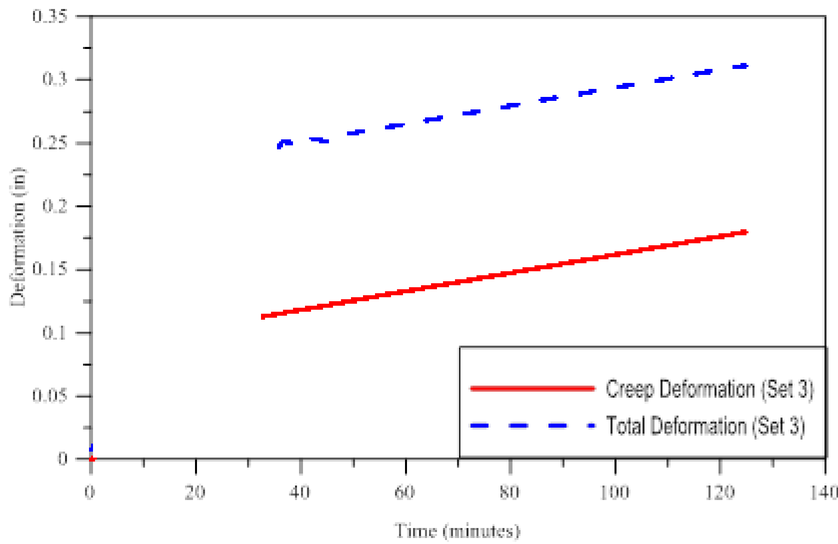


Figure 2.21: Total Deformation and Creep Deformation Curves for Set 3

Figures 2.19, 2.20 and 2.21show that the slope of the creep curve is higher at higher temperatures, i.e. slope of creep curve at 550^{o}C is higher than the slope at 500^{o}C and at 450^{o}C, respectively. This means that the creep rate increases as the temperature increases, in other words, more creep deformation happens at higher temperatures. It is clear that the creep is linear with constant slope; meaning that it did not reach the third stage. Since the stress and temperature are constants, the main factor affecting the creep is the time; the model that will be used to simulate the experiments will be the Modified Time-Hardening model.

2.8 Regression analysis

There are different regression models; linear and nonlinear. The model used in this thesis is the linear regression model, which can be either simple or multiple-regression model. [16]

The following equation represents the general form of **simple** linear regression model.

$y = \beta_o + \beta_1 x_1 + \epsilon$

x_n: Independent variables, regressor or predictor variables (Load, temperature and time)

y_n: Dependent variable, response variable (Deformation)

Where β_o and β_1 are constant parameters and ϵ is the error factor.

A simple linear regression model has a single regressor (x).

The following equation represents the general form of **multiple** linear regression model.

$y = \beta_o + \beta_1 x_1 + \ldots + \beta_n x_n + \epsilon$

x_n: Independent variables, regressor or predictor variables (Load, temperature and time)

y_n: Dependent variable, response variable (Deformation)

Where $\beta_o, \beta_1, \ldots, \beta_n$ are constant parameters and ϵ is the error factor.

A multiple linear regression model has multiple regressors (x's).

A linear regression model means that the model is linear within the parameters β_o, β_1, …, β_n not because (y) is a linear function of the (x's). (y) is related to the (x's) in a nonlinear fashion [16].

Regression analysis modeling was used in two processes. First, it was used to generate all the mathematical models. Second, it was used to normalize the deformation data. Due to the fact that temperature changes in cycles and the load had small changes throughout the experiment like in Figures 2.23 and 2.24 the LVDT reads the instantaneous deformation that is affected by the cycles of temperature change and the changes in load. This will produce a raw plot that needs normalization, like in Figure 2.22.

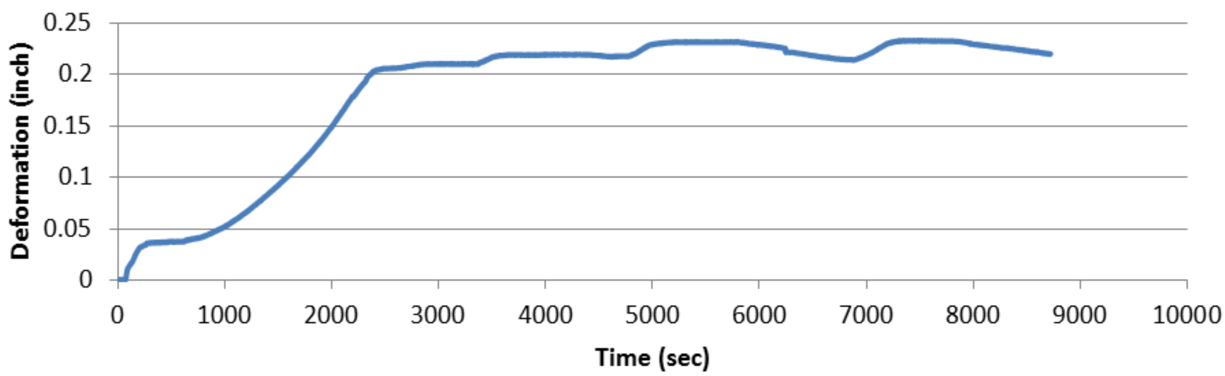


Figure 2.22: Total deformation of ASTM A325 bolt at exploratory experiment (450°C)

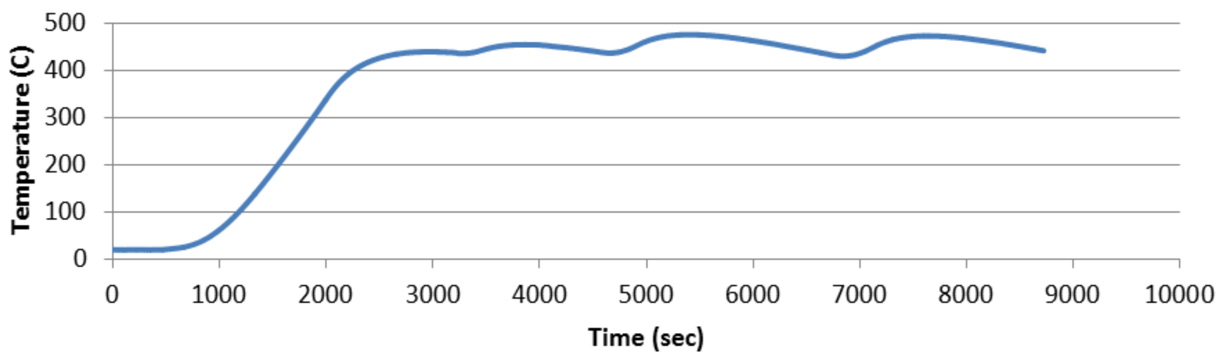


Figure 2.23: Temperature used at exploratory experiment (450°C)

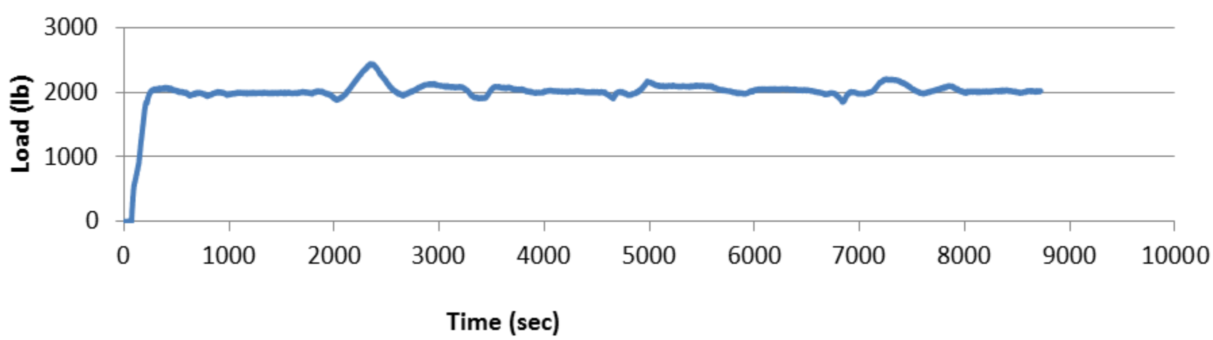


Figure 2.24: Load used at exploratory experiment (2000 lb)

Regression analysis is used to find a model that relates the deformation (y) to the variables; load (x_1) and temperature (x_2). This model can be used by substituting the desired values or load and temperature to obtain an accurate evaluation of the creep value.

Regression analysis can be done using different commercial software like STATISTICA, MATLAB, Microsoft Excel and many other statistical packages. As Microsoft Excel is widely used and available and can perform linear regression analysis it was used to perform regression analyses for this thesis.

After performing regression analysis for the data of the exploratory experiment in Figures 2.21, 2.22, and 2.23, the following plots were generated. Figure 2.25,and 2.26.

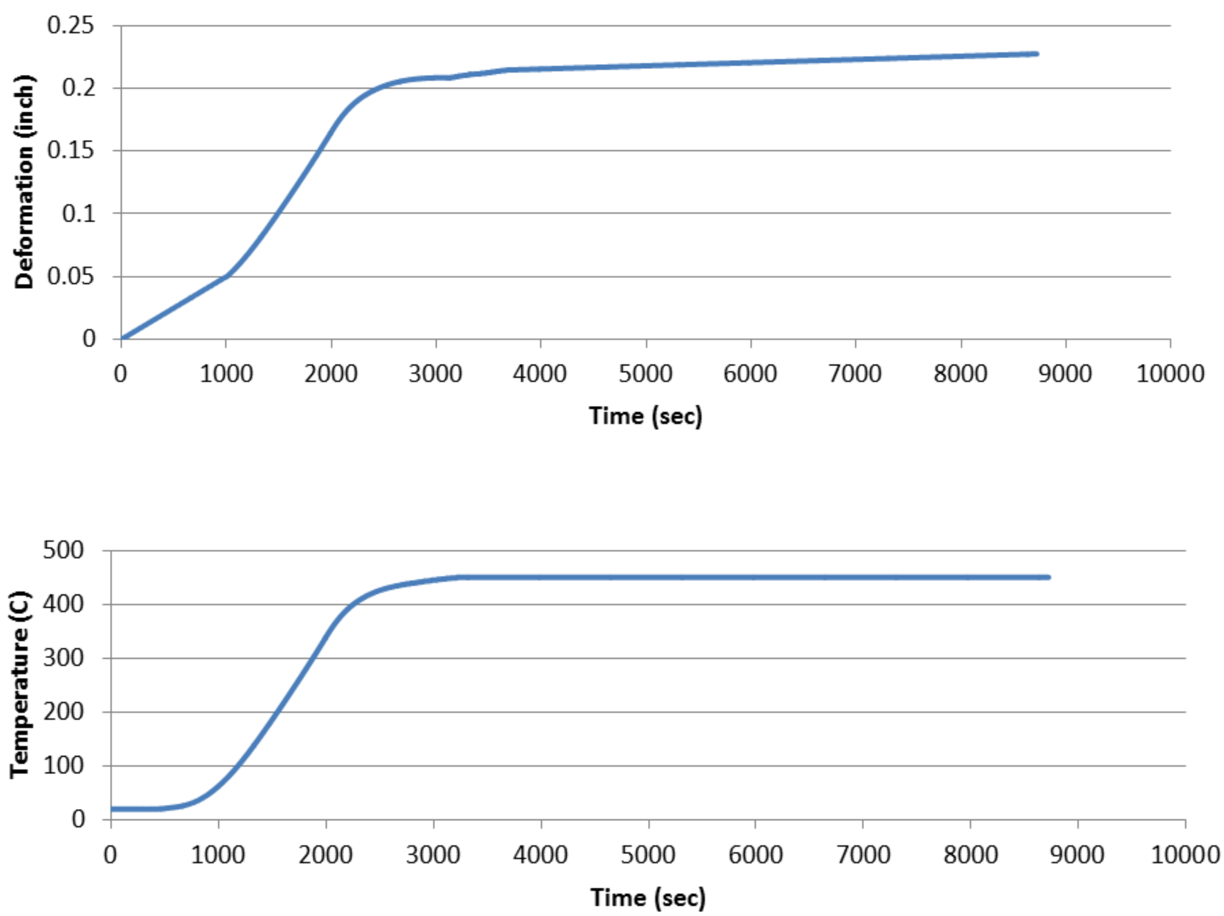


Figure 2.25: Normalized total deformation and temperature used at exploratory experiment (450°C)

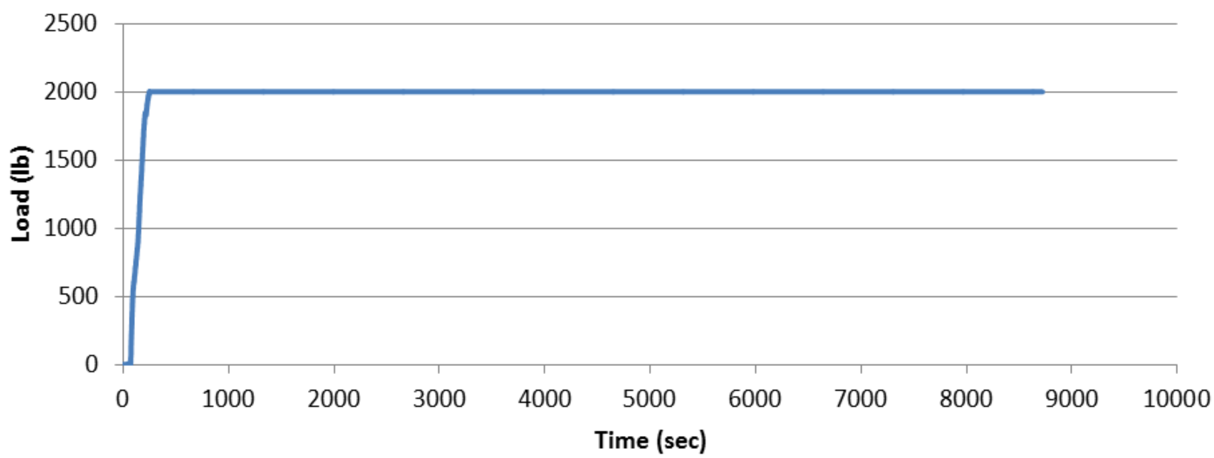


Figure 2.26: Normalized load used at exploratory experiment (2000 lb)

2.9 Developing Creep Models

Looking at the creep deformations in figures 2.19, 2.20, and 2.21, it can be noticed that the creep deformations exhibited in figures are linear after the temperatures and stresses became constant in each figure. This linear creep deformation represents the first stage of creep which is primary creep. Modified time hardening primary creep model (Equation 2.5) [17] was used to model the creep behavior.

$$\epsilon_{cr} = \frac{C_1 \sigma^{C_2} t^{C_3+1} e^{-C_4/T}}{C_3+1} \qquad \text{eq. (2.5)}$$

Where,

ϵ_{cr}: Strain due to creep

σ : Normal stress on the bolt

t : Time (seconds)

e: Natural logarithm base = 2.71828

T: Temperature (°C)

C_1, C_2, C_3 and C_4: constants

Linear regression analysis [16] was used to solve for the constants $C_1,\ C_2,\ C_3,$ and C_4 for each set of experiments. To solve for the constants, begin with linearization of the equation which was done by taking the logarithm of both sides of the equation as shown in Equation 2.6. Some logarithm properties were applied on the equation to shape it as shown in Equation 2.8.

$$\log(\epsilon_{cr}) = \log\left(C_1\sigma^{C_2}t^{C_3+1}e^{-C_4/T}\right) - \log(C_3+1) \quad \text{eq. (2.6)}$$

$$\log(\epsilon_{cr}) = \log(C_1)+\log(\sigma^{C_2}) + \log(t^{C_3+1}) + \log(e^{\frac{-C_4}{T}}) - \log(C_3+1) \quad \text{eq. (2.7)}$$

$$\log(\epsilon_{cr}) = \log(C_1)+C_2\log(\sigma) + (C_3+1)\log(t) - C_4\left(\frac{\log(e)}{T}\right) - \log(C_3+1) \quad \text{eq. (2.8)}$$

First set of experiments, T=450°C

Table 2-2. Model Constants for the First Set of Experiments (T=450°C)

C_1	0.000199
C_2	0.22242
C_3	-0.92865
C_4	246.5064

$$\epsilon_{cr} = \frac{0.000199\sigma^{0.22242}t^{-0.92865+1}e^{-246.5064/T}}{-0.92865+1}$$

Second set of experiments, T=500°C

Table 2-3. Model Constants for the Second Set of Experiments (T=500°C)

C_1	3.27E-07
C_2	0.854796
C_3	-0.77998
C_4	2.365149

$$\epsilon_{cr} = \frac{(3.27\mathrm{E}-07)\sigma^{0.854796}t^{-0.77998+1}e^{-2.365149/T}}{-0.77998+1}$$

Third set of experiments, T=550°C

Table 2-4. Model Constants for the Third Set of Experiments (T=550°C)

C_1	2.41E-07
C_2	0.821356
C_3	-0.51722
C_4	9.460976

$$\epsilon_{cr} = \frac{(2.41\mathrm{E}-07)\sigma^{0.821356}t^{-0.51722+1}e^{-9.460976/T}}{-0.51722+1}$$

Using the mathematical model of creep strain (Equation 2.5) and the creep constants corresponding to each set, predicted creep strain values were found and plots of predicted creep strain vs time for each set were generated. Figures 2.27, 2.28, and 2.29 show comparison between experimental creep strains and predicted creep strains. The figures show accurate prediction of creep strain values compared to the experimental creep strain values. This shows that model results successfully match the experimental results.

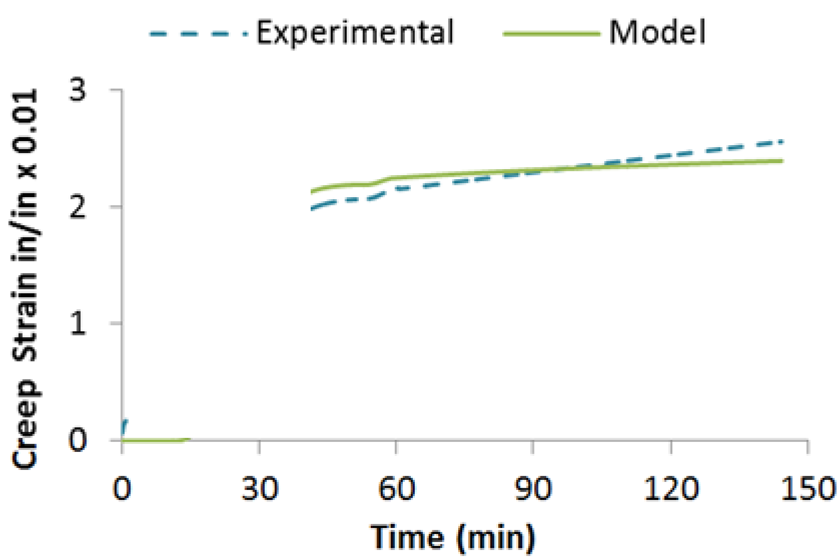


Figure 2.27.Comparison between Experimental Creep Strain and Creep Strain Predicted Using Modified Time Hardening Model of the First Set

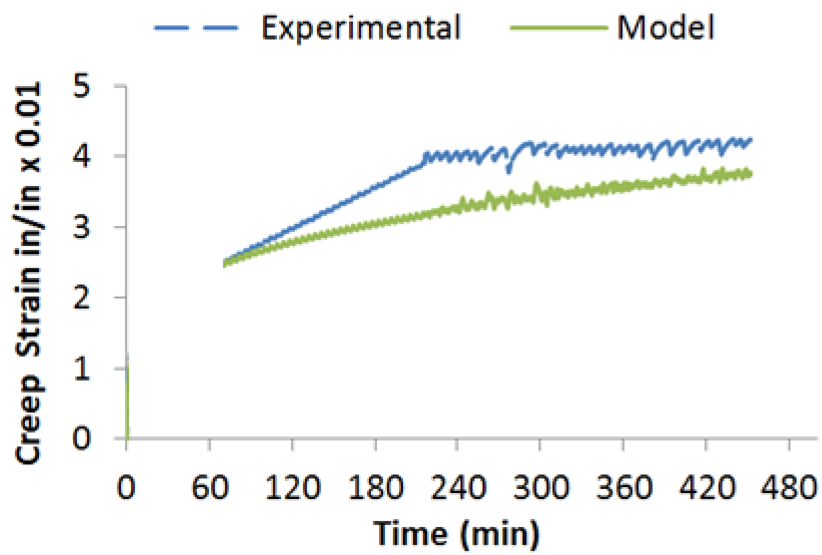


Figure 2.28.Comparison between Experimental Creep Strain and Creep Strain Predicted Using Modified Time Hardening Model of the Second Set

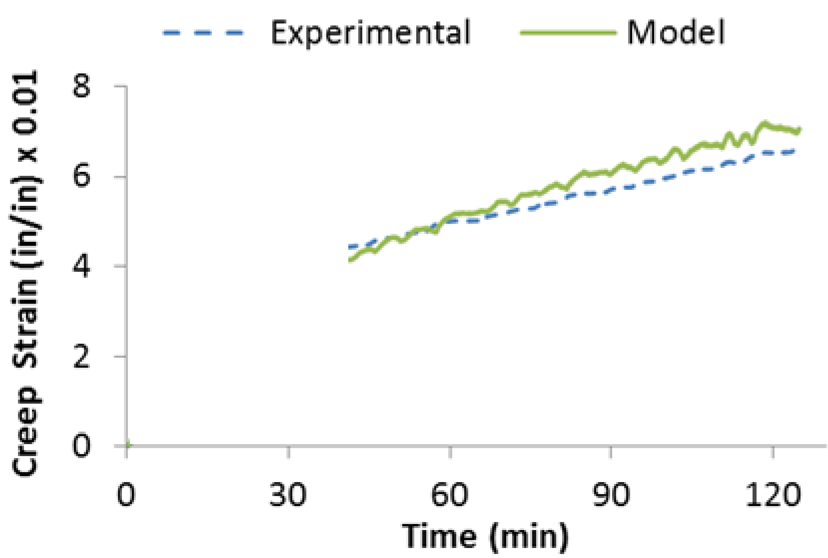


Figure 2.29.Comparison between Experimental Creep Strain and Creep Strain Predicted Using Modified Time Hardening Model of the Third Set

2.10 Coefficient of Determination

Coefficient of determination (R^2) is the square of the Pearson function (Coefficient of correlation) (R). It reflects the extent of a linear relationship between two data sets, where a value of 1 means that the two data sets make perfect correlation. The closer the value to 1, the better the correlation. The closer the value to zero, the worse the correlation. Coefficient of determination can be calculated using the following equation:

$$R = \frac{\sum(x-\bar{x})(y-\bar{y})}{\sum(x-\bar{x})^2\sum(y-\bar{y})^2} \qquad \text{eq. (2.9)}$$

For a strong correlation, R value should be higher than 0.8, and R2 should be higher than 0.64. [18]

2.11 General Model Using All Sets of Experiments

A generalized creep model can predict creep strain for the range of temperatures between 450°C and 550°C with strong correlation. The values of the four constants for the general model are reported in table 2-5. This model can still predict creep strain outside this range with lower accuracy.

Table 2-5 Constants for the General Creep Model

C1	1.8E-08
C2	0.923853
C3	-0.36659
C4	-13.8052

$$\epsilon_{cr} = \frac{(1.8E-08)\sigma^{0.923853}t^{-0.36659+1}e^{-(-13.8052)/T}}{-0.36659+1}$$

Experimental versus predicted creep strain values are plotted and the values of the coefficient of determination (R^2) are generated.

Figures 2.30, 2.31 and 2.32 show that the values of R^2 are all higher than 0.64 which shows that the model has strong correlation.

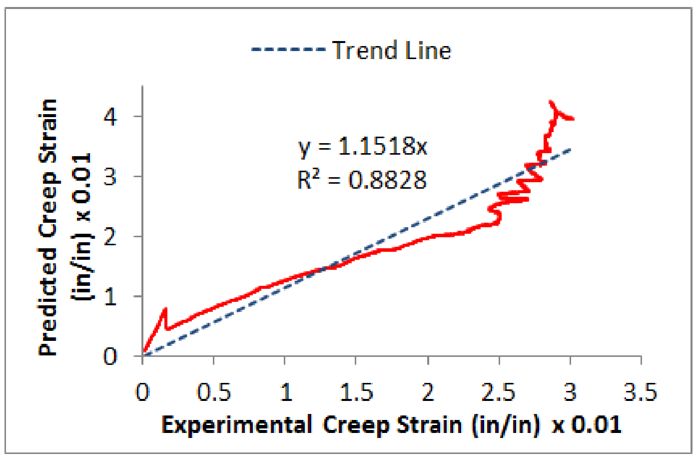


Figure 2.30. Experimental versus Predicted Creep Strain at T=450°C using the General Model

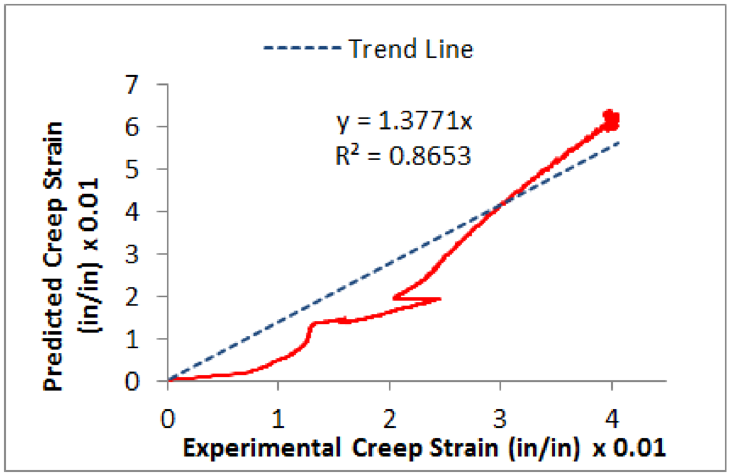


Figure 2.31. Experimental versus Predicted Creep Strain at T=500°C using the General Model

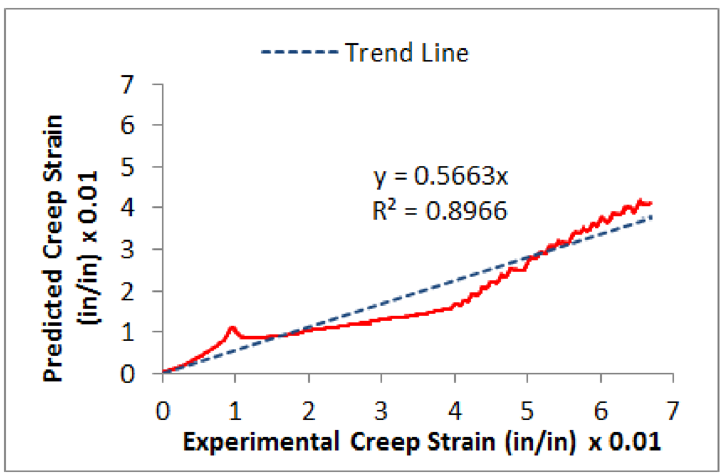


Figure 2.32. Experimental versus Predicted Creep Strain at T=550°C using the General Model

The creep constants of the general model represent the three temperatures (450°C, 500°C, and 550°C), it can be used to manually predict creep strains for non-constant temperature loading. The general model was generated since it is difficult to manually interpolate between the three models (450°C, 500°C, and 550°C) when trying to manually calculate the creep strain for a bolt under variable temperature. On the other hand, if finite element software is used to predict the creep behavior for a bolt with variable temperature loading, creep constants of each of the three sets can be entered to the software and it can perform the interpolation.

2.12 Using the general model to modify previous work

In previous work by Shrih (2013), tensile tests under high temperature on ASTM A325 bolts were performed. A finite element model was developed to simulate his experiments. Temperature-Displacement plots were generated; F.E. results deviates from experimental results at high temperatures. Since creep was not taken into consideration in his work, the general creep model will be used to adjust the F.E. curve by adding creep effect.

Data and results of Shrih’s work were acquired as shown in Figure 2.33. The general model was used to modify the F.E. curve. The model adjusted the F.E curve so that the deformation of F.E. curve matches those in experimental data curves, this is shown in Figure 2.34.

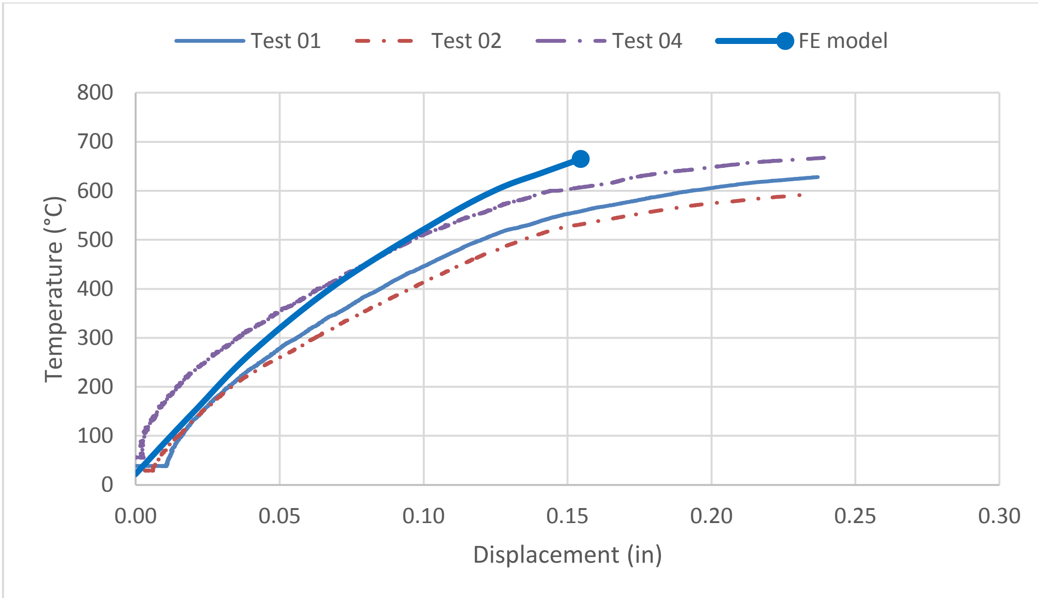


Figure 2.33: Temperature- Displacement comparison of Shrih's experiments and F.E. Model before adding creep effect

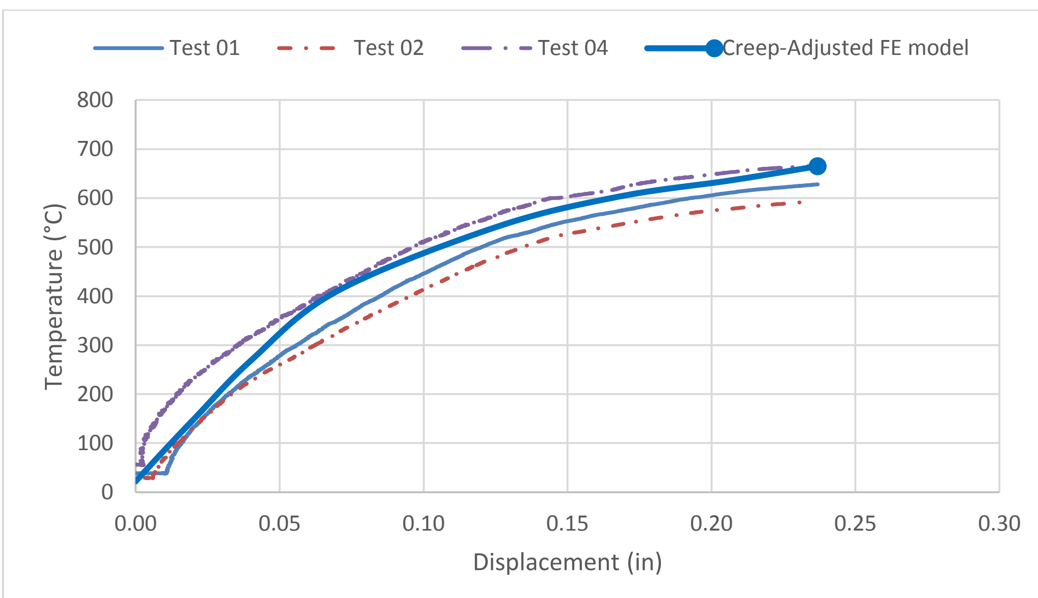


Figure 2.34: Temperature- Displacement comparison of Shrih's experiments and F.E. Model after adding creep effect to the F.E. Model

Chapter 3

The Finite Element Model of ASTM A325 Bolt

Finite element analysis is the most reliable simulation method. With all the finite element software available, it is easy to simulate any structural or mechanical behavior and find the results with high accuracy, assuming all inputs are accurate. Numerical solutions are no longer needed for stress-strain behavior analysis. All problems, from the simplest to the most complicated loading and geometry, can be routinely analyzed. Due to the usefulness of finite element analysis, modelling of the experiments performed in this research was done to compare the experimental and simulated results.

Three models were created using ANSYS Workbench to simulate each of the three sets of experiments. One representative experiment was chosen from each set to be simulated. Creep deformation is assumed to be exhibited on the bolt only. The reason for this is that the loading rods used in the setup have much larger diameter, in addition, most of the length is outside the chamber; which means they are under room temperature. Loading sections used in the experiment are thick compared to the bolt, they were assumed to exhibit no creep deformation. Because of the aforementioned reasons and for simplicity, the only part of the experimental setup that was modelled is the bolt. The bolt was modelled as a cylinder, which represents the geometry of the body of the bolt. Since the other parts of the setup (channel sections and rods) used in the experimental work were not modelled, their deformation will be calculated manually and added to the results generated from these models. The experimental total deformation will be compared to the deformation resulted by FE simulation.

All the three models have the same geometry, meshing, mechanical loading and material properties. The differences between the models are experimental time intervals and temperature loading. Time interval and temperature loading were taken from the experimental data of the selected representative experiments to make the comparison meaningful. A summary of how each case was modelled is shown below. Full details are shown in the appendix.

3.1 Model Geometry

The same geometry was used in all models, which is the geometry of the bolt only. A cylinder of diameter of (0.5 in) and a length of (2.69 in) was used, as shown in Figure 3.1. The (2.69 in) is the length of the bolt without the threaded part or the head of the bolt. The total length of the bolt used is (4 in), the threaded part is (1 in), and the head thickness is (5/16 in). The head of the bolt and the threaded part are assumed to have negligible deformations relative to the shaft of the bolt.

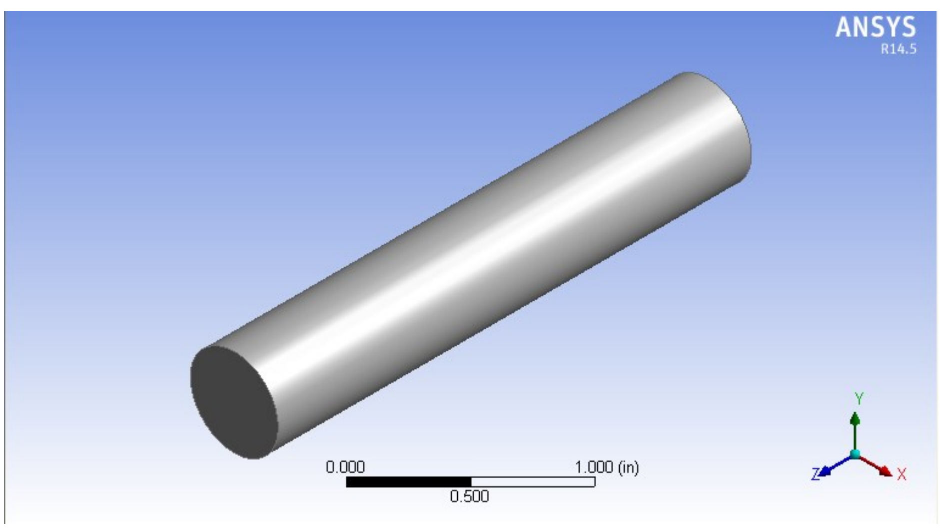


Figure 3.1 Geometry of the bolt

3.2 Creating the Mesh

ANSYS workbench has an automatic meshing option. A coarse, medium, or fine mesh option can be selected and ANSYS workbench determines the appropriate size of elements and the appropriate element type.

The model used is a cylinder; this means the meshing of this model is simple and straightforward. There is no sudden change in geometry which means there is no refinement needed for the mesh. A medium sized mesh was used in all models. Figure 3.2 shows the model after meshing. Table 3-1 shows the number of nodes and elements generated due to using a medium size mesh.

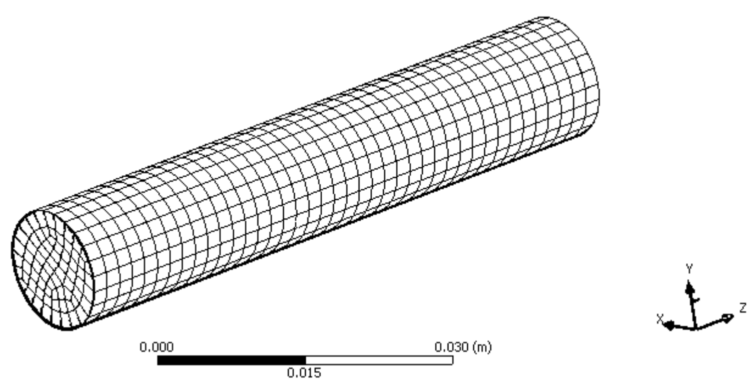


Figure 3.2 Bolt mesh

Table 3-1: Model Statistics

Statistics	
Nodes	12955
Elements	2800

3.3 Load Steps

Three load steps were assigned for each model. Each step represents a change in loading. The 2000-lb-load was applied to the bolt on the first step. The first loading step in FE model was assumed to have taken one second in all models. Temperature was applied gradually during the second model. Heating tabular data was taken from the experimental results and copied into a table in ANSYS which will apply the temperature at the corresponding time as per the entered tabular data. This loading step has different time duration in each model, since the time intervals in each experiment is different. The third loading step represents the time interval at which the temperature was constant. This loading step also has different time length in each model due to the difference in time period of each experiment.

Tables 3-2, 3-3, and 3-4 show the end time of each step for the three models. End time for each load step is based on the data obtained from the experimental results for each set of experiments. This means that the times used in the F.E. model is identical to that in the experiment.

Table 3-2: End time for each load step for the first model (450^{o} C)

Step	Step Description	Step End Time (seconds)
1	Application of 2000-lb-load	1
2	Application of thermal load from room temperature to (450^{o} C)	3530
3	Constant temperature (450^{o} C) until the end of experiment time	8656

Table 3-3: End time for each load step for the second model (500^{o} C)

Step	Step Description	Step End Time (seconds)
1	Application of 2000-lb-load	1
2	Application of thermal load from room temperature to (500^{o} C)	3097
3	Constant temperature (500^{o} C) until the end of experiment time	12966

Table 3-4: End time for each load step for the third model (550^{o} C)

Step	Step Description	Step End Time (seconds)
1	Application of 2000-lb-load	1
2	Application of thermal load from room temperature to (500^{o} C)	3670
3	Constant temperature (550^{o} C) until the end of experiment time	10662

3.4 Application of mechanical load, thermal load and boundary conditions

Constant pressure was applied on the bolt in all three of the models, where the other side of the bolt was fixed as shown in Figures 3.3 and 3.4. The constant pressure assigned is the pressure that results from applying 2000 lb force on a circular section with a diameter of 0.5 in. Thermal load was applied during three load steps to the surface and conducted in.. The first stage of thermal loading was applied during the first loading step in the FE model. The first loading step represents the model under room temperature. The second loading step represents heating the model up to 450^{o} C in the first model, 500^{o} C in the second model, and 550^{o} C in the third model.

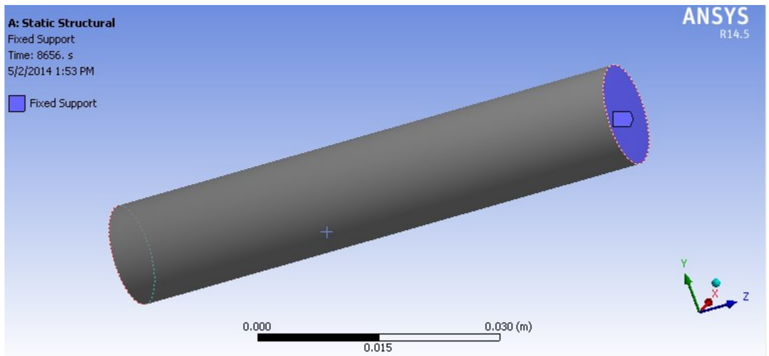


Figure 3.3 Assigning of a fixed support for all models

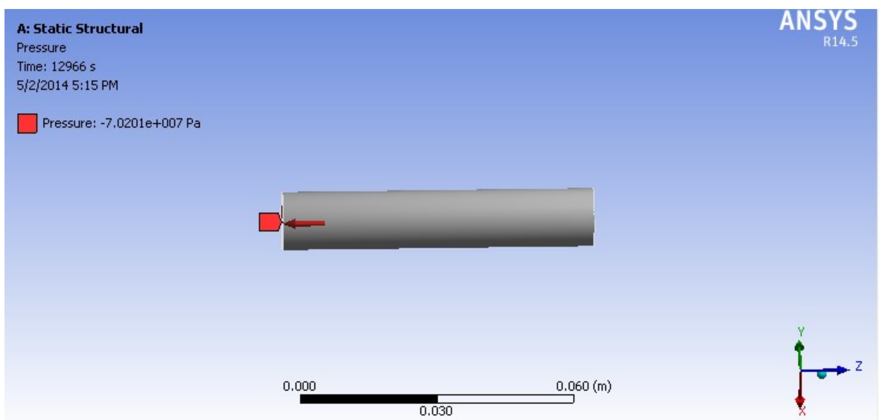


Figure 3.4 Application of constant tension pressure on the model

3.5 Deformation Results

Total deformations results of the bolt for each model were generated in the results report. Total deformation in each model is the deformation of the bolt only under mechanical loading, temperature loading, and creep effect for the bolt at load steps explained previously. Figures 3.5, 3.6, and 3.7 show the resulted deformations. Figures show maximum deformations of 0.0522 in, 0.0734 in, and 0.163 in at the temperatures 450° C, 500° C, and 550° C, respectively. It is clear that the total deformation increases with increasing temperature which makes sense and matches the theory and experimental data.

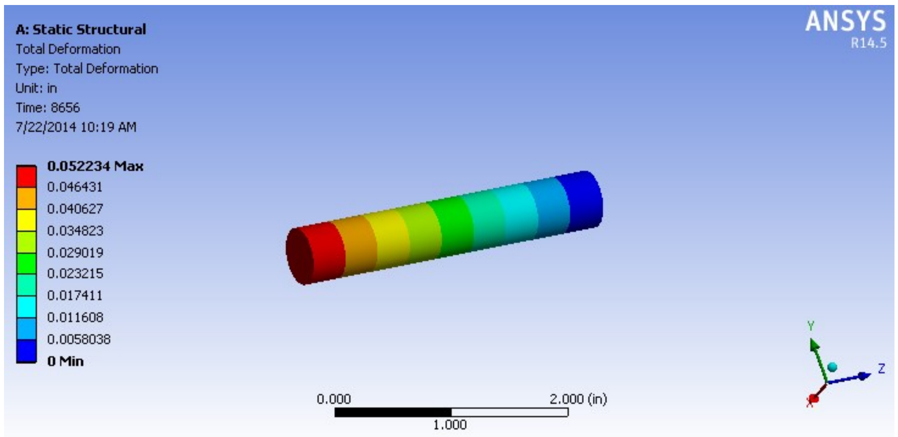


Figure 3.5 Deformation results for the first model at temperature of (450° C)

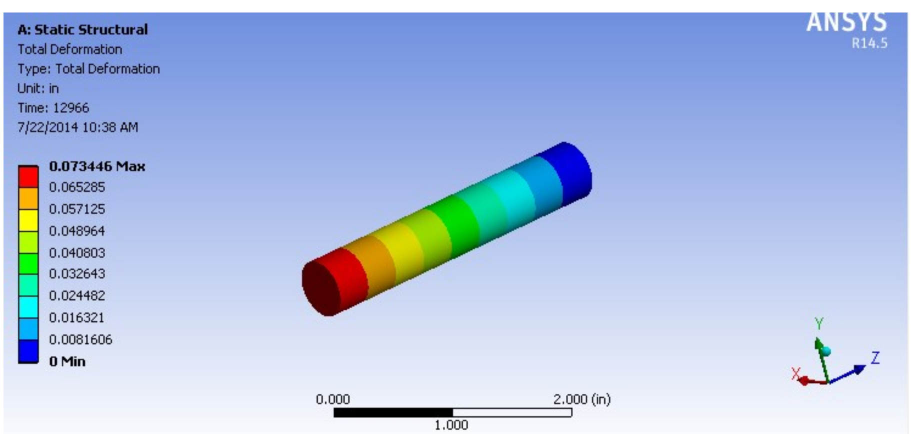


Figure 3.6 Deformation results for the second model at temperature of (500° C)

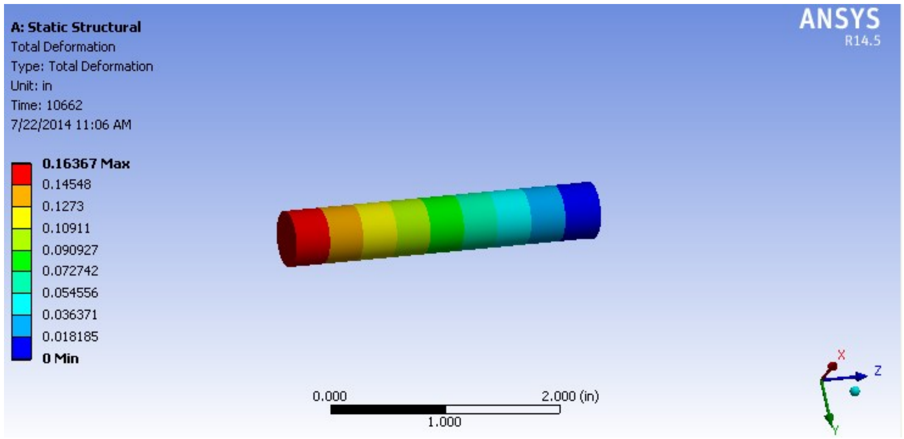


Figure 3.7 Deformation results for the third model at temperature of (550^{o} C)

3.6 Creep Strain Results

Creep strain results on the bolt for the each model are shown in Figures 3.8 through 3.10. Creep strain shown in the results of these models is the creep strain of the bolt only. The figures show maximum creep strain of 0.0138, 0.021, and 0.0603 at the temperatures 450^{o} C, 500^{o} C, and 550^{o} C, respectively. By examining the results, we can conclude that creep strain or creep deformation increases with increasing temperature which matches the theory and the experimental data.

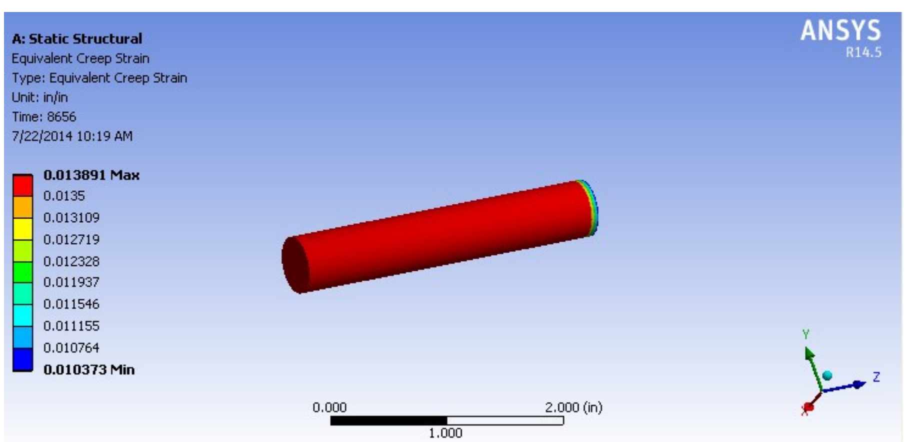


Figure 3.8 Creep strain results for the first model at temperature of (450^{o} C)

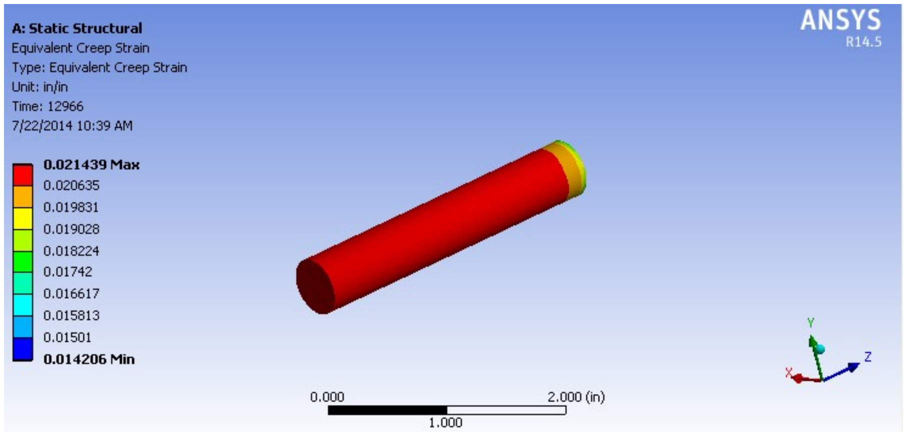


Figure 3.9 Creep strain results for the second model at temperature of (500^o C)

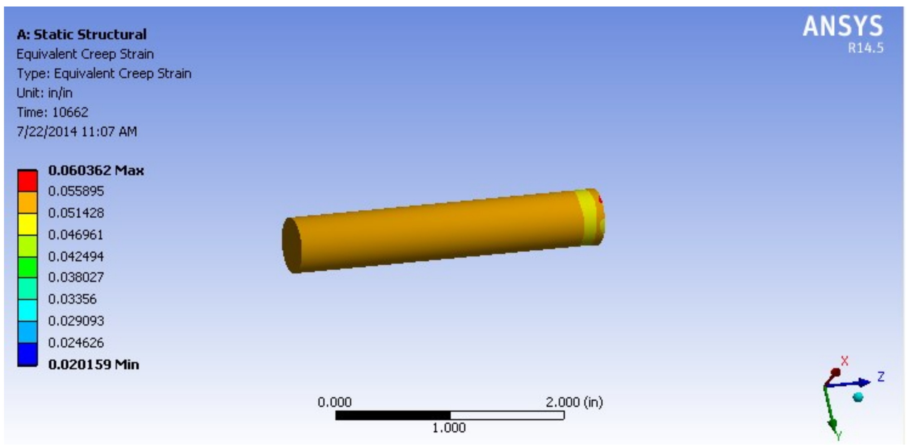


Figure 3.10 Creep strain results for the third model at temperature of (550^o C)

3.7 Comparison between experimental results and finite element results

Since FE models represent the bolt only, the results represent bolt deformation only. The deformations of square channel sections and rods were manually calculated and added to the FE results. Deformation of rods consists of two types of deformations; deformation due to temperature and deformation due to mechanical loading. Equations used to find thermal deformations and mechanical load deformations are represented by Equations 3.1 and 3.2, respectively.

$\delta_T = \alpha\ \Delta T\ L$ ……… Eq. 3.1

$\delta_{Load} = \frac{P\ L}{A\ E}$ ………… Eq. 3.2

Deformation of sections can be calculated by adding up the thermal deformation and mechanical loading deformation. Thermal expansion is assumed to be exhibited on the sides of the sections. Mechanical loading exhibited on the top and bottom parts of each channel section is assumed to create simply-supported beams. All of the top and bottom parts were assumed to be simply-supported beam with a fixed concentrated load at mid-span as shown in Figure 3.11. Deformation exhibited due to thermal expansions on the sides of both sections were found using Equation 3.1. Simply-supported beam deformation can be calculated using Equation 3.3.

$\delta_{\text{simply-supported beam}} = \frac{PL^3}{48\ EI}$ …….. Eq. 3.3

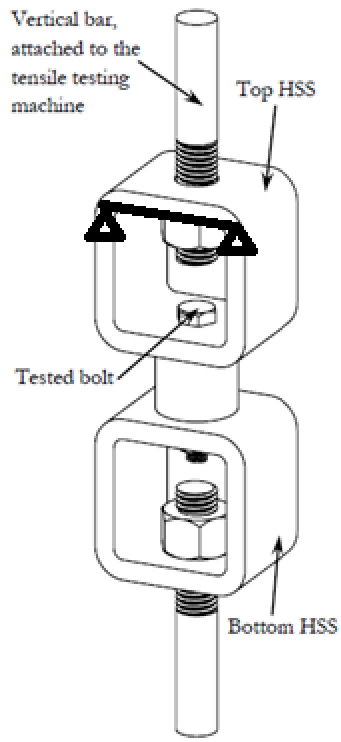


Figure 3.11 Simply-supported beam

Where,

δ_T = Thermal expansion

δ_{Load} = Deformation due to mechanical load

α = Coefficient of thermal expansion

ΔT = Change in temperature

L = Length

P = Load

A = Area of cross section

E = Elastic modulus

I = Moment of inertia of the cross section

The entire model can be combined into one equation; total deformation of the whole setup can be expressed as:

$$\delta_{Total} = \delta_{bolt\text{- }ANSYS} + \delta_{T,\text{ two loading rods}} + \delta_{T,\text{ sections sides}} + \delta_{Load,\text{ top and bottom of sections}} + \delta_{Load,\text{ rods}} + \delta_{Load,\text{ sections sides}}$$

Figures 3.12, 3.13, and 3.14 show the comparisons between the deformation curves attained from experimental data and those from FE results. FE curves in all figures represent accurate evaluation of experimental results curves. All FE models match the experimental data with acceptable accuracy. Error may be due to the fact that the function of rate of heating used in the FE model is just an approximation of the experimental rate of heating.

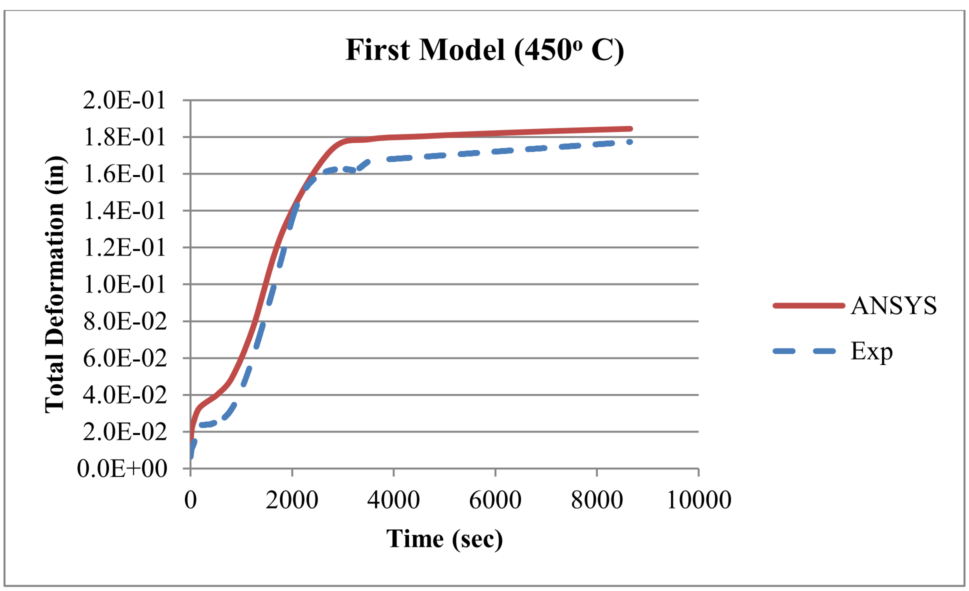


Figure 3.12 Comparison between experimental and FE deformation curves for the first model

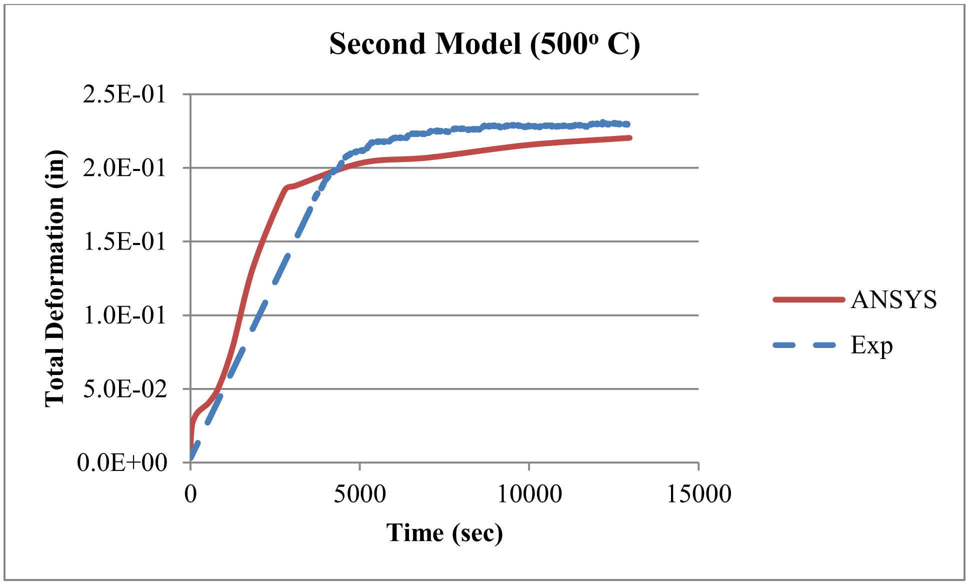


Figure 3.13 Comparison between experimental and FE deformation curves for the second model

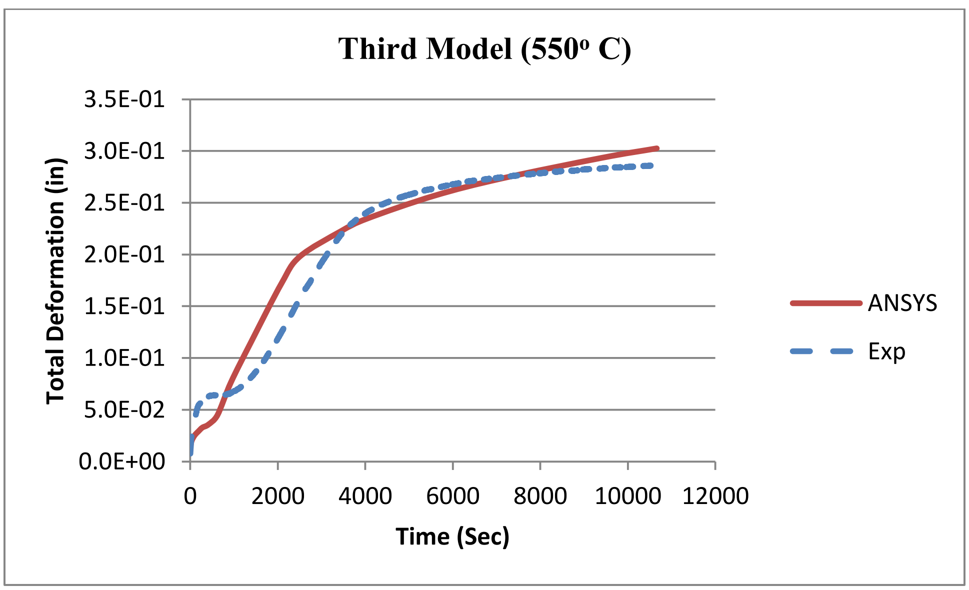


Figure 3.14 Comparison between experimental and FE deformation curves for the third model

Chapter 4

Summary of Completed Work and Conclusions

4.1 Summary of Completed Work

In this work, primary creep of ASTM A325 bolt under high temperature condition was studied. Experiments and finite element analysis were performed.

Three sets of experiments were performed in this study. The experiments performed were tension testing of ASTM A325 under constant stress and constant high temperature. The stress was the same in the three sets of experiments while the temperatures varied from 450^{o} C to 550^{o} C. Testing equipment and details of the experiments were discussed in detail in chapter 1. From these experiments, deformation-time curves were plotted. The results were also used to calculate and plot the creep deformation in the bolt for each experiment. Calculation of creep deformation was performed by subtracting the summation of deformation that is a result of mechanical load and the deformation that is a result of change in temperature for the whole assembly from the total deformation.

The outcomes of this investigation are numerical methods to evaluate creep strain under high temperature and constant mechanical load. Four computational models to predict creep strain were formulated. Three models to calculate creep strain under constants temperatures 450^{o} C, 500^{o} C, and 550^{o} C were formulated in order to be used in finite element analysis using ANSYS. These models were developed using one of the built-in formulas in ANSYS Work Bench. The models were evaluated by performing finite element modelling of the experiments and comparing the experimental work to the finite element model. One model was developed to be used in manual calculation; this model was referred to as the “General Model” in this thesis. The general model was used to modify a previous finite element analysis work done by Shrih (2013). The general model was evaluated by comparison with the experimental work that was done by Shrih in the same aforementioned work.

4.2 Conclusions

1) Creep constants that were found in this study were used to perform finite element analysis of the experimental work. The analysis was found to predict the experiments with reasonable accuracy.

2) The general creep model that was developed in this study was found to accurately adjust the finite element analysis that was done in a previous work by Shrih (2013).

3) Prediction of steel under high temperature in the finite element model required accounting for creep as nonlinear behavior. It also requires the temperature dependent material properties represented by modulus of elasticity and shear modulus.

4) Comparison of the adjusted finite element curve and the experiment performed in Shrih (2013) work was made. The comparison showed that the computational model that was used to adjust the curve was a good prediction of creep strain.

5) Comparisons of experimental work performed in this study and the simulated finite element models were made. The comparisons showed that the creep constants used for the model simulation produced results with reasonable accuracy.

4.3 Suggestions for further experimentation

1. The use of different assemblies with fewer parts to decrease inaccuracies resulted from deformations of loading fixtures.
2. The use of different assembly made of alternate materials with higher temperature tolerances. The assembly used in the experiments performed in this study shows plastic deformations at temperature in the range of 600^{o}C. Using a stronger assembly that can behave linearly at temperatures higher than 600^{o}C will allow the study of secondary and possibly tertiary creep deformation.
3. Using a different method for heating the bolt. This can be achieved by using a heating coil to heat the bolt only. This prevents thermal deformations in the setup parts which will lead to fewer inaccuracies that might happen.

4.4 Limitations of Developed Models and Constants

A constant load of 2000 lb on a 0.5 in bolt was used in all experiments. This means that the equations developed work accurately to predict creep strain at the same stress used in this study.

The temperature range used in the experiments was limited due to the strength of the used setup. This means that the model and constants developed will work within the same range.

4.5 Future Work

1. Models and constants developed in this study work on the same conditions used in the experiments which developed these models. More experimental work is needed at a

wider range of stresses in order to be able to predict creep strain at different loads or different diameters. Since the stress depends on the load and cross-sectional area, a wide range of stresses can be achieved by using different value of load for each experiment or it can also be achieved by using different bolt diameter for each experiment. This will allow for the development of dimensionless curves that will account for a wide range of dimensions and loads.

2. The temperature range in this study was limited due to the fact that the setup used did not perform as expected at temperatures higher than 600^{o} C. Performing the same type of experiment using different setup and different heating method that would heat the bolt only would be more accurate. It will allow the experiment to reach secondary and possibly tertiary creep stages. This will also eliminate any uncertainties in the results that might happen due to creeping of parts other than the bolt.
3. The same kind of work taking the suggestions mentioned above can be performed on different types of bolts. A490, another common bolt, is expected to have a different creep behavior than A325 bolt.
4. The same kind of experiment can be performed on bolts that have undergone simulated earthquake deformation. Fire is not uncommon after every major earthquake due to failures in gas lines. Simulated earthquake effect can be performed on bolts before performing high temperature creep test. Different earthquake signatures can be used.
5. Development of dimensionless graphs with curves that represent different stresses and temperature. These graphs can predict the values of creep constants. Different graphs can be developed for different materials.

References

[1] Shrih, A. (2013). Experimental and finite element investigation of tension-loaded ASTM A325 bolts under simulated fire. Doctoral dissertation, University of Wisconsin-Milwaukee.

[2] N. Torić, A. Harapin & I. Boko. (2013). Experimental Verification of a Newly Developed Implicit Creep Model for Steel Structures Exposed to Fire. *Engineering Structures, Vol. 57, 116-124.*

[3] M.E. Kassner, M.T. Perez-Prado (2004), Fundamentals of Creep in Metals and Alloys, *Elsevier Ltd*, 2004

[4] F. W. McClintock & F. A. Argon. (1996). Mechanical Behavior of Materials. Addison Wesley Press.

[5] Eurocode 3. (2001). Design of Steel Structures: General rules – Structural fire design. ENV 1993-1-2, European Committee for Standardisation, Brussels.

[6] V. K. R. Kodur & M. M. S. Dwaikat. (2010). Effect of High Temperature Creep on the Fire Response of Restrained Steel Beams. *Materials and Structures*. 43:1327–1341

[7] Zhe Leng & David P. Field (2012), Damage susceptibility of grain boundaries in HT9 steel subjected to high-temperature creep. *Metallurgical and Materials Transaction A, Vol. 43A, 3539-3546.*

[8] Harmathy T (1967), A comprehensive creep model. *J Basic Eng 98(D-3): 496-502.*

[9] Harmathy T and Stanzak W (1970), Elevated-temperature tensile and creep properties of some structural and prestressing steels. *American Society for Testing and Materials: STP 464 P. 186-208*

[10] Anderberg Y (1988), Modelling steel behaviour. *Fire Safety J, 13(1) : 17-26*

[11] Shames IH, Cozzarelli FA (1992), Elastic and inelastic stress analysis. Prentice Hall, Englewood Cliffs, NJ, PP 221-228

[12] V. K. R. Kodur, M.M.S. Dwaikat (2010), Effect of high temperature creep on the fire response of restrained steel beams. *Materials and Structures. 43:1327-1341*

[13] [ANSYS, Inc. *ANSYS Workbench Documentation*, Version 14.0.]

[14] ASTM, SAE and ISO grade markings and mechanical properties for steel fasteners, American Fasteners Technologies Corporation, www.americanfastener.com

[15] Mohammad Matar et al. (2014) Primary creep in ASTM A325 bolts under simulated fire loading, *International Journal of Engineering Research & Innovation*. Spring/Summer 2014 Volume 6, Number 1.

[16] Douglas C. Montgomery, Elizabeth A. Peck & G. Geoffrey Vining (2012). Introduction to Linear Regression Analysis (4th ed.) Wiley-Interscience.

[17] F.H. Norton. (1929). Creep of Steel at High Temperatures, McGraw-Hill, New York.

[18] Schervish, M. J., & DeGroot, M. H. (2010), Probability and Statistics (4th ed.). Addison Wesley.

[19] Adeeb Rahman, Thomas Urbanik, and Mustafa Mahamid (2005), FE analysis of creep and hygroexpansion response of a corrugated fiberboard to a moisture flow: A Transit nonlinear analysis. *Wood and Fiber Science*, January 2006, V. 38(1).

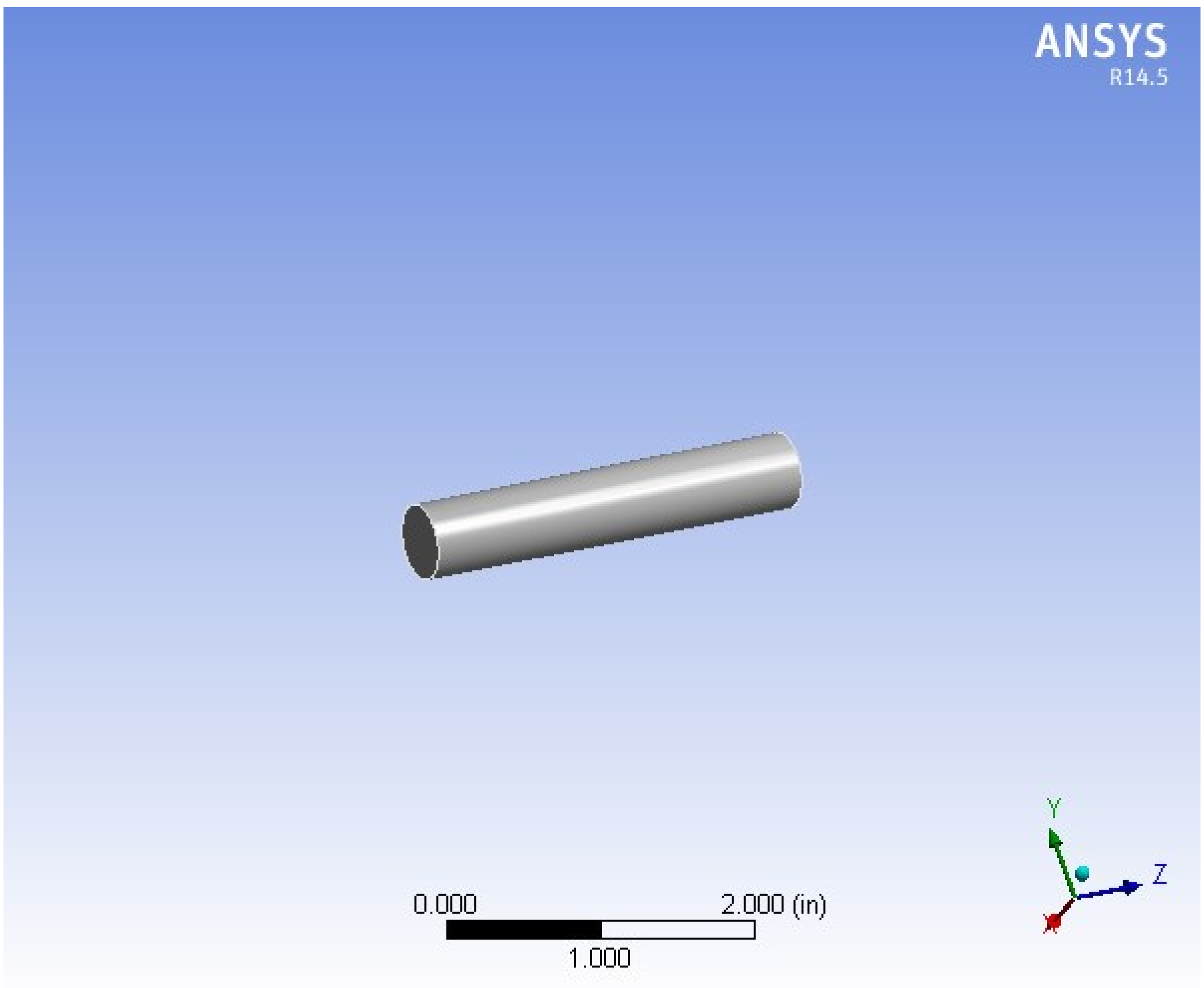
[20] G. Williams-Leir (1983), Creep of structural steel in fire: Analytical Expressions. *Fire and Materials*, Vol. 7, No. 2 1983.

[21] J. E. Dorn (1954), Some fundamental experiments on high temperature creep. *Journal of the Mechanics and Physics of Solids*, 1954, Vol. 3, pp. 85 to 116.

Appendix: ANSYS models details

First Model (450^{o} C)

Product Version	14.5.7 Release



Contents

Units

TABLE 1

Unit System	U.S. Customary (in, lbm, lbf, s, V, A) Degrees rad/s Fahrenheit
Angle	Degrees
Rotational Velocity	rad/s
Temperature	Fahrenheit

Model (A4)

Geometry

TABLE 2
Model (A4) > Geometry

Object Name	*Geometry*
State	Fully Defined
Definition	
Type	DesignModeler
Length Unit	Inches
Element Control	Program Controlled
Display Style	Body Color

Bounding Box	
Length X	0.5 in
Length Y	0.5 in
Length Z	2.69 in
Properties	
Volume	0.52818 in³
Mass	0.14979 lbm
Scale Factor Value	1.
Statistics	
Bodies	1
Active Bodies	1
Nodes	12955
Elements	2800
Mesh Metric	None
Basic Geometry Options	
Parameters	Yes
Parameter Key	DS
Attributes	No
Named Selections	No
Material Properties	No
Advanced Geometry Options	
Use Associativity	Yes
Coordinate Systems	No
Reader Mode Saves Updated File	No
Use Instances	Yes

Smart CAD Update	No
Attach File Via Temp File	Yes
Analysis Type	3-D
Decompose Disjoint Geometry	Yes
Enclosure and Symmetry Processing	Yes

TABLE 3
Model (A4) > Geometry > Parts

Object Name	*Solid*
State	Meshed
Graphics Properties	
Visible	Yes
Transparency	1
Definition	
Suppressed	No
Stiffness Behavior	Flexible
Coordinate System	Default Coordinate System
Reference Temperature	By Environment
Material	
Assignment	Structural Steel
Nonlinear Effects	Yes
Thermal Strain Effects	Yes
Bounding Box	
Length X	0.5 in
Length Y	0.5 in
Length Z	2.69 in
Properties	

Volume	0.52818 in^3
Mass	0.14979 lbm
Centroid X	5.2267e-018 in
Centroid Y	1.9256e-018 in
Centroid Z	1.345 in
Moment of Inertia Ip1	9.2184e-002 lbm·in^2
Moment of Inertia Ip2	9.2184e-002 lbm·in^2
Moment of Inertia Ip3	4.6337e-003 lbm·in^2
Statistics	
Nodes	12955
Elements	2800
Mesh Metric	None

Coordinate Systems

TABLE 4
Model (A4) > Coordinate Systems > Coordinate System

Object Name	*Global Coordinate System*
State	Fully Defined
Definition	
Type	Cartesian
Coordinate System ID	0.
Origin	
Origin X	0. in
Origin Y	0. in
Origin Z	0. in
Directional Vectors	
X Axis Data	[1. 0. 0.]

Y Axis Data	[0. 1. 0.]
Z Axis Data	[0. 0. 1.]

Mesh

TABLE 5
Model (A4) > Mesh

Object Name	*Mesh*
State	Solved
Defaults	
Physics Preference	Mechanical
Relevance	0
Sizing	
Use Advanced Size Function	Off
Relevance Center	Medium
Element Size	Default
Initial Size Seed	Active Assembly
Smoothing	Medium
Transition	Fast
Span Angle Center	Coarse
Minimum Edge Length	1.57080 in
Inflation	
Use Automatic Inflation	None
Inflation Option	Smooth Transition
Transition Ratio	0.272
Maximum Layers	5
Growth Rate	1.2
Inflation Algorithm	Pre

View Advanced Options	No
Patch Conforming Options	
Triangle Surface Mesher	Program Controlled
Advanced	
Shape Checking	Standard Mechanical
Element Midside Nodes	Program Controlled
Straight Sided Elements	No
Number of Retries	Default (4)
Extra Retries For Assembly	Yes
Rigid Body Behavior	Dimensionally Reduced
Mesh Morphing	Disabled
Defeaturing	
Pinch Tolerance	Please Define
Generate Pinch on Refresh	No
Automatic Mesh Based Defeaturing	On
Defeaturing Tolerance	Default
Statistics	
Nodes	12955
Elements	2800
Mesh Metric	None

Static Structural (A5)

TABLE 6
Model (A4) > Analysis

Object Name	*Static Structural (A5)*
State	Solved
Definition	

Physics Type	Structural
Analysis Type	Static Structural
Solver Target	Mechanical APDL
Options	
Environment Temperature	71.6 °F
Generate Input Only	No

TABLE 7
Model (A4) > Static Structural (A5) > Analysis Settings

Object Name	*Analysis Settings*
State	Fully Defined
Step Controls	
Number Of Steps	3.
Current Step Number	3.
Step End Time	8656. s
Auto Time Stepping	Program Controlled
Solver Controls	
Solver Type	Program Controlled
Weak Springs	Program Controlled
Large Deflection	Off
Inertia Relief	Off
Restart Controls	
Generate Restart Points	Program Controlled
Retain Files After Full Solve	No
Creep Controls	
Creep Effects	On
Nonlinear Controls	

Force Convergence	Program Controlled
Moment Convergence	Program Controlled
Displacement Convergence	Program Controlled
Rotation Convergence	Program Controlled
Line Search	Program Controlled
Stabilization	Off
Output Controls	
Stress	Yes
Strain	Yes
Nodal Forces	No
Contact Miscellaneous	No
General Miscellaneous	No
Store Results At	All Time Points
Max Number of Result Sets	1000.
Analysis Data Management	
Future Analysis	None
Scratch Solver Files Directory	
Save MAPDL db	No
Delete Unneeded Files	Yes
Nonlinear Solution	Yes
Solver Units	Active System
Solver Unit System	Bin

TABLE 8
Model (A4) > Static Structural (A5) > Analysis Settings
Step-Specific "Step Controls"

Step	Step End Time

1	1. s
2	3530. s
3	8656. s

TABLE 9
Model (A4) > Static Structural (A5) > Analysis Settings
Step-Specific "Creep Controls"

Step	Creep Effects	Creep Limit Ratio
1	Off	
2	On	100.
3	On	100.

TABLE 10
Model (A4) > Static Structural (A5) > Analysis Settings
Step-Specific "Output Controls"

Step	Max Number of Result Sets
1	Program Controlled
2	1000.
3	

TABLE 11
Model (A4) > Static Structural (A5) > Loads

Object Name	*Pressure*	*Fixed Support*	*Thermal Condition*
State	Fully Defined		
Scope			
Scoping Method	Geometry Selection		
Geometry	1 Face		1 Body
Definition			
Type	Pressure	Fixed Support	Thermal Condition
Define By	Normal To		
Magnitude	Tabular Data		Tabular Data

Suppressed	No		
Tabular Data			
Independent Variable	Time		Time

FIGURE 1
Model (A4) > Static Structural (A5) > Pressure

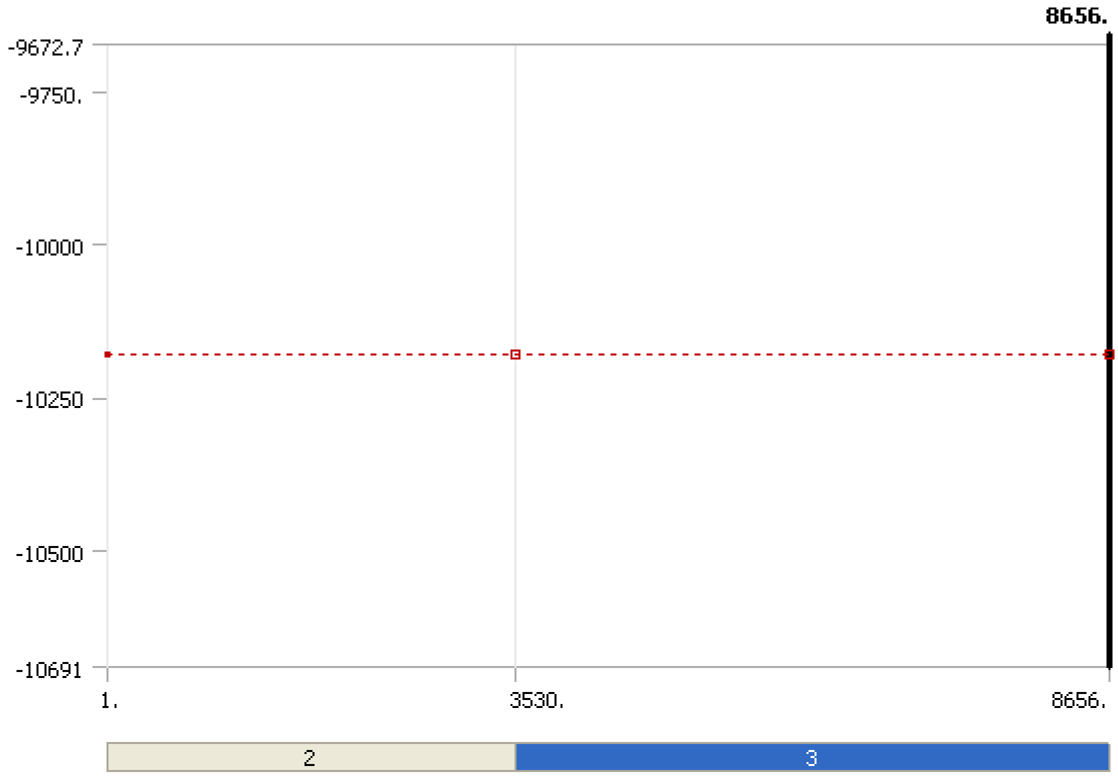


TABLE 12
Model (A4) > Static Structural (A5) > Pressure

Steps	Time [s]	Pressure [psi]
1	0.	-10182
	1.	
2	3530.	= -10182
3	8656.	

FIGURE 2
Model (A4) > Static Structural (A5) > Thermal Condition

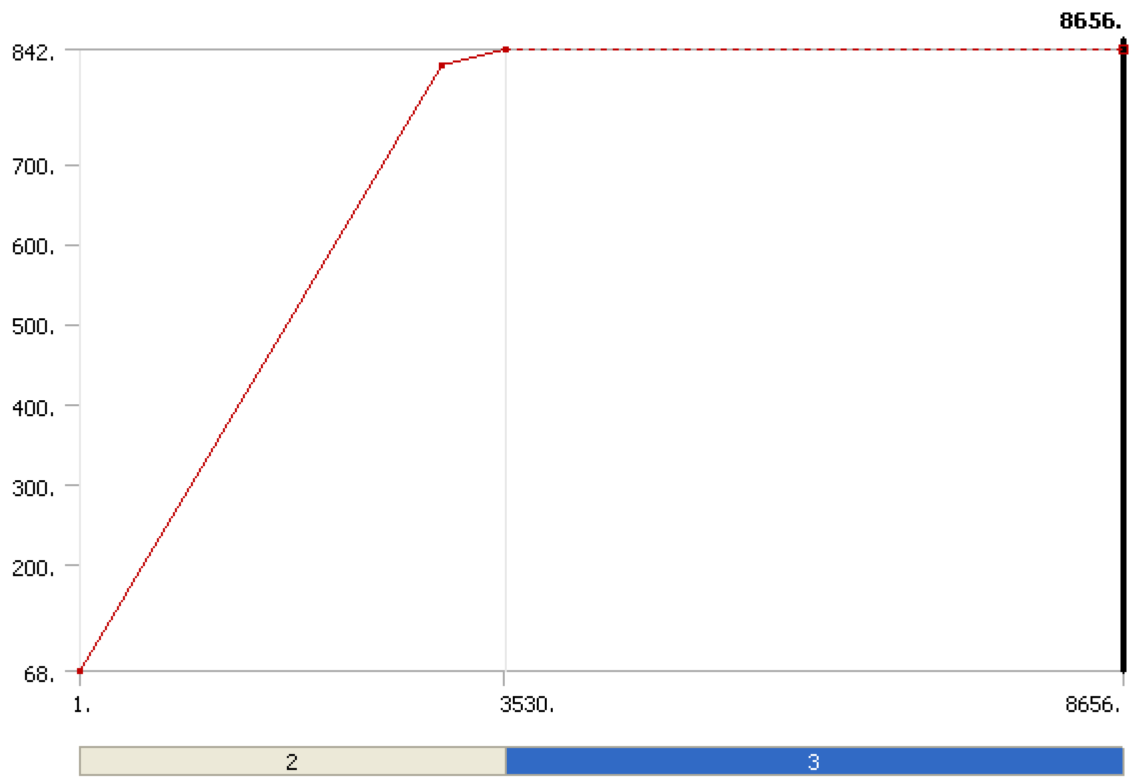


TABLE 13
Model (A4) > Static Structural (A5) > Thermal Condition

Steps	Time [s]	Temperature [°F]
1	0.	68.
	1.	
2	3000.	822.2
	3530.	842.
3	8656.	= 842.

Solution (A6)

TABLE 14
Model (A4) > Static Structural (A5) > Solution

Object Name	*Solution (A6)*
State	Solved
Adaptive Mesh Refinement	
Max Refinement Loops	1.

Refinement Depth	2.
Information	
Status	Done

TABLE 15
Model (A4) > Static Structural (A5) > Solution (A6) > Solution Information

Object Name	*Solution Information*
State	Solved
Solution Information	
Solution Output	Solver Output
Newton-Raphson Residuals	0
Update Interval	2.5 s
Display Points	All
FE Connection Visibility	
Activate Visibility	Yes
Display	All FE Connectors
Draw Connections Attached To	All Nodes
Line Color	Connection Type
Visible on Results	No
Line Thickness	Single
Display Type	Lines

TABLE 16
Model (A4) > Static Structural (A5) > Solution (A6) > Results

Object Name	*Equivalent Plastic Strain*	*Total Deformation*	*Equivalent Creep Strain*
State	Solved		
Scope			
Scoping Method	Geometry Selection		

Geometry	All Bodies		
Definition			
Type	Equivalent Plastic Strain	Total Deformation	Equivalent Creep Strain
By	Time		
Display Time	Last		
Calculate Time History	Yes		
Identifier			
Suppressed	No		
Integration Point Results			
Display Option	Averaged		Averaged
Results			
Minimum	0. in/in	0. in	1.0373e-002 in/in
Maximum	0. in/in	5.2234e-002 in	1.3891e-002 in/in
Minimum Value Over Time			
Minimum	0. in/in	0. in	0. in/in
Maximum	0. in/in	0. in	1.0373e-002 in/in
Maximum Value Over Time			
Minimum	0. in/in	8.7451e-004 in	0. in/in
Maximum	0. in/in	5.2234e-002 in	1.3891e-002 in/in
Information			
Time	8656. s		
Load Step	3		
Substep	4		
Iteration Number	69		

FIGURE 3
Model (A4) > Static Structural (A5) > Solution (A6) > Equivalent Plastic Strain

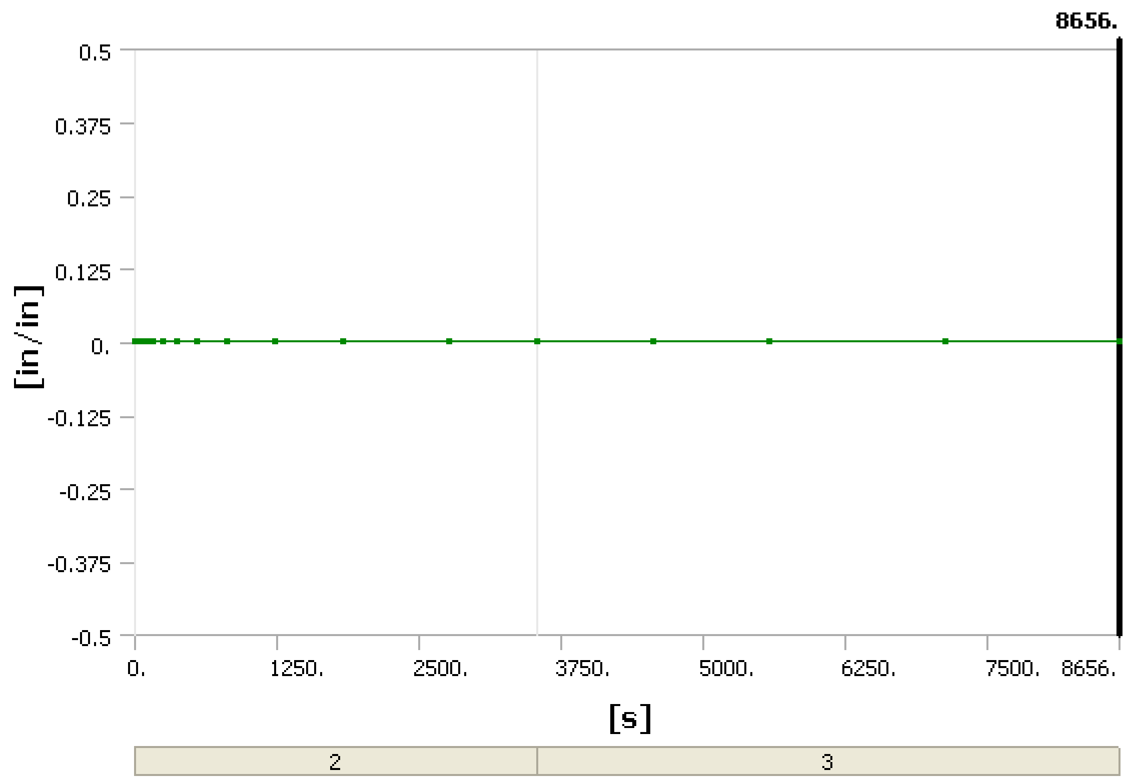


TABLE 17
Model (A4) > Static Structural (A5) > Solution (A6) > Equivalent Plastic Strain

Time [s]	Minimum [in/in]	Maximum [in/in]
0.2	0.	0.
0.4		
0.7		
1.		
4.529		
8.058		
11.587		
16.58		
23.65		
34.255		
50.162		

74.023		
109.81		
163.5		
244.03		
364.83		
546.02		
817.81		
1225.5		
1837.		
2754.3		
3530.		
4555.2		
5580.4		
7118.2		
8656.		

FIGURE 4
Model (A4) > Static Structural (A5) > Solution (A6) > Total Deformation

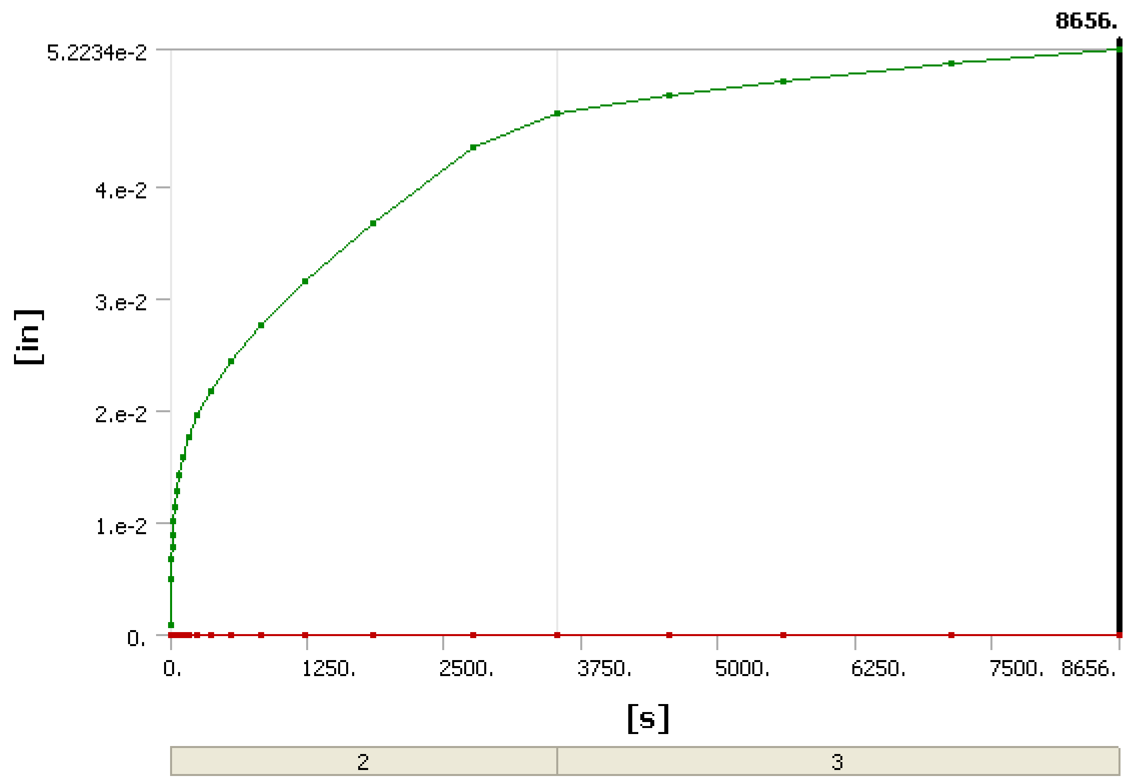


TABLE 18
Model (A4) > Static Structural (A5) > Solution (A6) > Total Deformation

Time [s]	Minimum [in]	Maximum [in]
0.2	0.	8.7451e-004
0.4		
0.7		
1.		
4.529		5.0184e-003
8.058		6.73e-003
11.587		7.852e-003
16.58		8.9953e-003
23.65		1.0169e-002
34.255		1.1441e-002
50.162		1.2814e-002

74.023		1.4292e-002
109.81		1.5895e-002
163.5		1.765e-002
244.03		1.9607e-002
364.83		2.1835e-002
546.02		2.4442e-002
817.81		2.7617e-002
1225.5		3.158e-002
1837.		3.6682e-002
2754.3		4.3465e-002
3530.		4.6551e-002
4555.2		4.8129e-002
5580.4		4.9409e-002
7118.2		5.0962e-002
8656.		5.2234e-002

FIGURE 5
Model (A4) > Static Structural (A5) > Solution (A6) > Equivalent Creep Strain

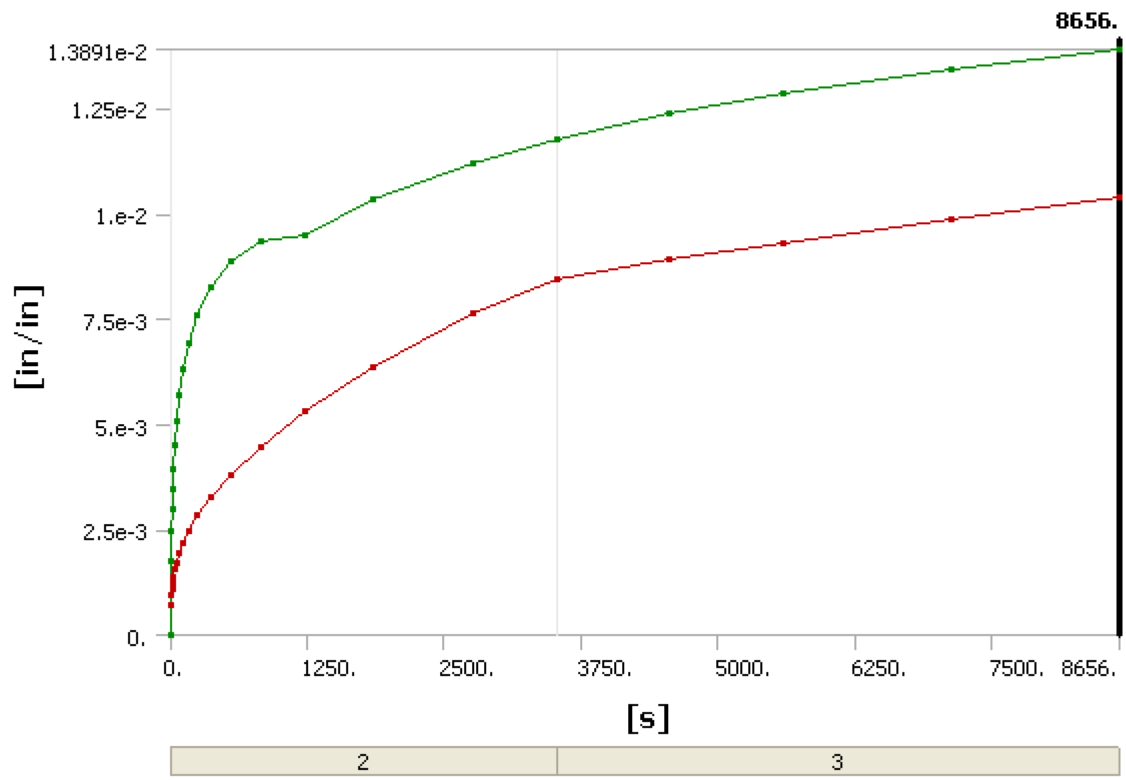


TABLE 19
Model (A4) > Static Structural (A5) > Solution (A6) > Equivalent Creep Strain

Time [s]	Minimum [in/in]	Maximum [in/in]
0.2	0.	0.
0.4		
0.7		
1.		
4.529	7.3195e-004	1.7524e-003
8.058	9.5231e-004	2.4852e-003
11.587	1.0908e-003	2.9667e-003
16.58	1.2316e-003	3.457e-003
23.65	1.3786e-003	3.9578e-003
34.255	1.5427e-003	4.496e-003
50.162	1.7275e-003	5.0669e-003

74.023	1.9385e-003	5.6668e-003
109.81	2.184e-003	6.2926e-003
163.5	2.4753e-003	6.9404e-003
244.03	2.8275e-003	7.6042e-003
364.83	3.26e-003	8.2688e-003
546.02	3.7981e-003	8.8889e-003
817.81	4.4734e-003	9.3301e-003
1225.5	5.3196e-003	9.4919e-003
1837.	6.3682e-003	1.0315e-002
2754.3	7.6366e-003	1.1204e-002
3530.	8.4423e-003	1.1774e-002
4555.2	8.9289e-003	1.2366e-002
5580.4	9.2816e-003	1.2842e-002
7118.2	9.851e-003	1.342e-002
8656.	1.0373e-002	1.3891e-002

Material Data

Structural Steel

TABLE 20
Structural Steel > Constants

Density	0.2836 lbm in^-3
Coefficient of Thermal Expansion	6.6667e-006 F^-1
Specific Heat	0.10366 BTU lbm^-1 F^-1
Thermal Conductivity	8.0917e-004 BTU s^-1 in^-1 F^-1
Resistivity	8.5235 ohm cmil in^-1

TABLE 21
Structural Steel > Compressive Ultimate Strength

Compressive Ultimate Strength psi
0

TABLE 22
Structural Steel > Compressive Yield Strength

Compressive Yield Strength psi
36259

TABLE 23
Structural Steel > Tensile Yield Strength

Tensile Yield Strength psi
36259

TABLE 24
Structural Steel > Tensile Ultimate Strength

Tensile Ultimate Strength psi
66717

TABLE 25
Structural Steel > Isotropic Secant Coefficient of Thermal Expansion

Reference Temperature F
71.6

TABLE 26
Structural Steel > Alternating Stress Mean Stress

Alternating Stress psi	Cycles	Mean Stress psi
5.8001e+005	10	0
4.1002e+005	20	0
2.7499e+005	50	0
2.0494e+005	100	0
1.5505e+005	200	0
63962	2000	0
38000	10000	0

31038	20000	0
20015	1.e+005	0
16534	2.e+005	0
12502	1.e+006	0

TABLE 27
Structural Steel > Strain-Life Parameters

Strength Coefficient psi	Strength Exponent	Ductility Coefficient	Ductility Exponent	Cyclic Strength Coefficient psi	Cyclic Strain Hardening Exponent
1.3343e+005	-0.106	0.213	-0.47	1.4504e+005	0.2

TABLE 28
Structural Steel > Isotropic Elasticity

Temperature F	Young's Modulus psi	Poisson's Ratio	Bulk Modulus psi	Shear Modulus psi
71.6	2.9008e+007	0.3	2.4173e+007	1.1157e+007
212	2.9008e+007	0.3	2.4173e+007	1.1157e+007
392	2.6107e+007	0.3	2.1756e+007	1.0041e+007
572	2.3206e+007	0.3	1.9338e+007	8.9254e+006
752	2.0305e+007	0.3	1.6921e+007	7.8097e+006
932	1.7405e+007	0.3	1.4504e+007	6.694e+006
1112	8.9923e+006	0.3	7.4936e+006	3.4586e+006
1292	3.771e+006	0.3	3.1425e+006	1.4504e+006
1472	2.6107e+006	0.3	2.1756e+006	1.0041e+006
1652	1.96e+006	0.3	1.6333e+006	7.5385e+005

TABLE 29
Structural Steel > Isotropic Relative Permeability

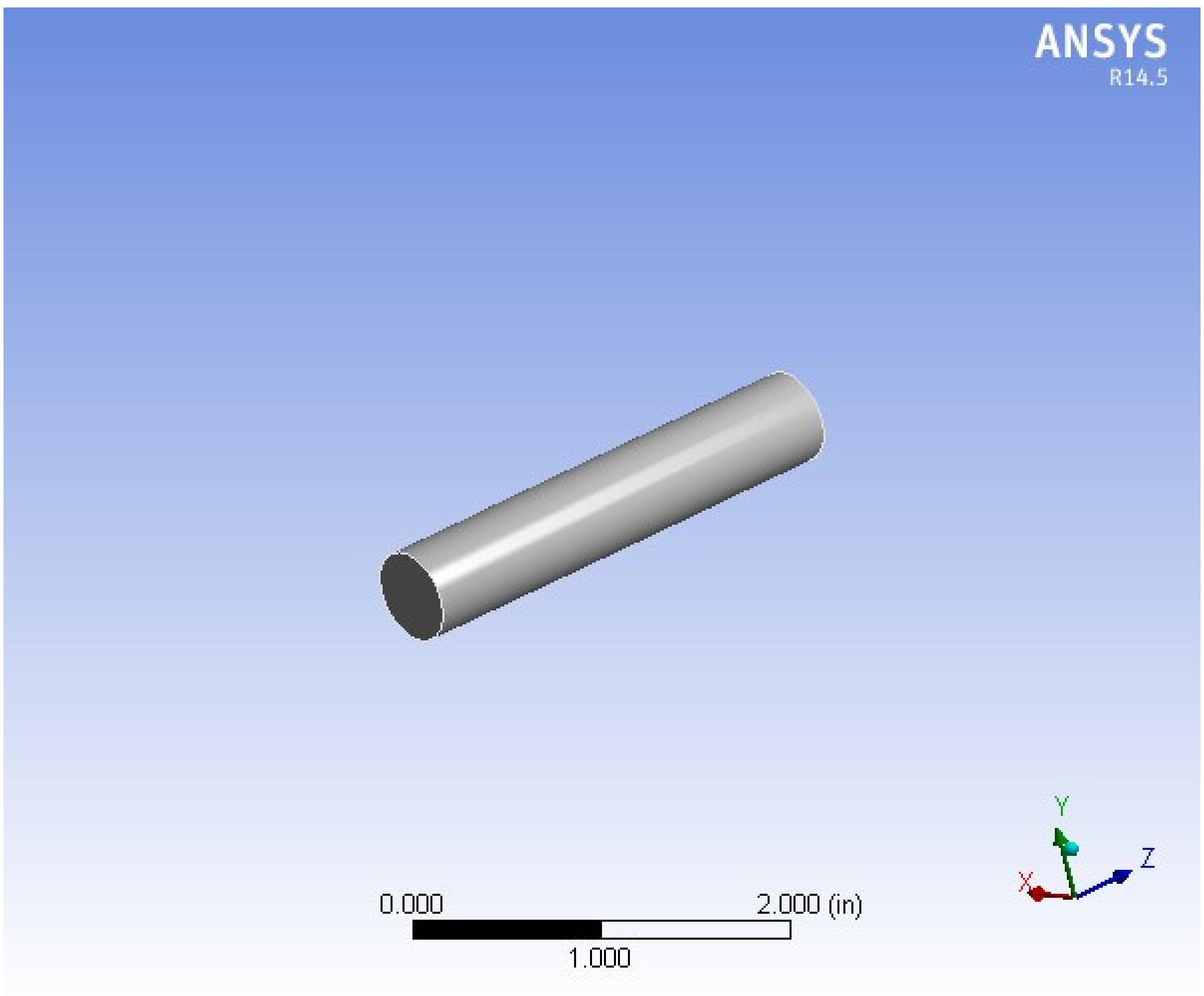
Relative Permeability
10000

TABLE 30
Structural Steel > Modified Time Hardening

Temperature F	Creep Constant 1	Creep Constant 2	Creep Constant 3	Creep Constant 4
842	1.99e-004	0.22242	-0.92865	246.51
932	3.27e-007	0.8548	-0.77998	2.3651
1022	2.41e-007	0.82136	-0.51722	9.461

Second Model (500^{o} C)

Product Version	14.5.7 Release



Contents

Units

TABLE 1

Unit System	U.S. Customary (in, lbm, lbf, s, V, A) Degrees rad/s Fahrenheit
Angle	Degrees
Rotational Velocity	rad/s
Temperature	Fahrenheit

Model (A4)

Geometry

TABLE 2
Model (A4) > Geometry

Object Name	*Geometry*
State	Fully Defined
Definition	
Type	DesignModeler
Length Unit	Inches
Element Control	Program Controlled
Display Style	Body Color

Bounding Box	
Length X	0.5 in
Length Y	0.5 in
Length Z	2.69 in
Properties	
Volume	0.52818 in³
Mass	0.14979 lbm
Scale Factor Value	1.
Statistics	
Bodies	1
Active Bodies	1
Nodes	12955
Elements	2800
Mesh Metric	None
Basic Geometry Options	
Parameters	Yes
Parameter Key	DS
Attributes	No
Named Selections	No
Material Properties	No
Advanced Geometry Options	
Use Associativity	Yes
Coordinate Systems	No
Reader Mode Saves Updated File	No
Use Instances	Yes

Smart CAD Update	No
Attach File Via Temp File	Yes
Analysis Type	3-D
Decompose Disjoint Geometry	Yes
Enclosure and Symmetry Processing	Yes

TABLE 3
Model (A4) > Geometry > Parts

Object Name	*Solid*
State	Meshed
Graphics Properties	
Visible	Yes
Transparency	1
Definition	
Suppressed	No
Stiffness Behavior	Flexible
Coordinate System	Default Coordinate System
Reference Temperature	By Environment
Material	
Assignment	Structural Steel
Nonlinear Effects	Yes
Thermal Strain Effects	Yes
Bounding Box	
Length X	0.5 in
Length Y	0.5 in
Length Z	2.69 in
Properties	

Volume	0.52818 in³
Mass	0.14979 lbm
Centroid X	5.2267e-018 in
Centroid Y	1.9256e-018 in
Centroid Z	1.345 in
Moment of Inertia Ip1	9.2184e-002 lbm·in²
Moment of Inertia Ip2	9.2184e-002 lbm·in²
Moment of Inertia Ip3	4.6337e-003 lbm·in²
Statistics	
Nodes	12955
Elements	2800
Mesh Metric	None

Coordinate Systems

TABLE 4
Model (A4) > Coordinate Systems > Coordinate System

Object Name	*Global Coordinate System*
State	Fully Defined
Definition	
Type	Cartesian
Coordinate System ID	0.
Origin	
Origin X	0. in
Origin Y	0. in
Origin Z	0. in
Directional Vectors	
X Axis Data	[1. 0. 0.]

Y Axis Data	[0. 1. 0.]
Z Axis Data	[0. 0. 1.]

Mesh

TABLE 5
Model (A4) > Mesh

Object Name	*Mesh*
State	Solved
Defaults	
Physics Preference	Mechanical
Relevance	0
Sizing	
Use Advanced Size Function	Off
Relevance Center	Medium
Element Size	Default
Initial Size Seed	Active Assembly
Smoothing	Medium
Transition	Fast
Span Angle Center	Coarse
Minimum Edge Length	1.57080 in
Inflation	
Use Automatic Inflation	None
Inflation Option	Smooth Transition
Transition Ratio	0.272
Maximum Layers	5
Growth Rate	1.2
Inflation Algorithm	Pre

View Advanced Options	No
Patch Conforming Options	
Triangle Surface Mesher	Program Controlled
Advanced	
Shape Checking	Standard Mechanical
Element Midside Nodes	Program Controlled
Straight Sided Elements	No
Number of Retries	Default (4)
Extra Retries For Assembly	Yes
Rigid Body Behavior	Dimensionally Reduced
Mesh Morphing	Disabled
Defeaturing	
Pinch Tolerance	Please Define
Generate Pinch on Refresh	No
Automatic Mesh Based Defeaturing	On
Defeaturing Tolerance	Default
Statistics	
Nodes	12955
Elements	2800
Mesh Metric	None

Static Structural (A5)

TABLE 6
Model (A4) > Analysis

Object Name	*Static Structural (A5)*
State	Solved
Definition	

Physics Type	Structural
Analysis Type	Static Structural
Solver Target	Mechanical APDL
Options	
Environment Temperature	71.6 °F
Generate Input Only	No

TABLE 7
Model (A4) > Static Structural (A5) > Analysis Settings

Object Name	*Analysis Settings*
State	Fully Defined
Step Controls	
Number Of Steps	3.
Current Step Number	3.
Step End Time	12966 s
Auto Time Stepping	Program Controlled
Solver Controls	
Solver Type	Program Controlled
Weak Springs	Program Controlled
Large Deflection	Off
Inertia Relief	Off
Restart Controls	
Generate Restart Points	Program Controlled
Retain Files After Full Solve	No
Creep Controls	
Creep Effects	On
Nonlinear Controls	

Force Convergence	Program Controlled
Moment Convergence	Program Controlled
Displacement Convergence	Program Controlled
Rotation Convergence	Program Controlled
Line Search	Program Controlled
Stabilization	Off
Output Controls	
Stress	Yes
Strain	Yes
Nodal Forces	No
Contact Miscellaneous	No
General Miscellaneous	No
Store Results At	All Time Points
Max Number of Result Sets	1000.
Analysis Data Management	
Future Analysis	None
Scratch Solver Files Directory	
Save MAPDL db	No
Delete Unneeded Files	Yes
Nonlinear Solution	Yes
Solver Units	Active System
Solver Unit System	Bin

TABLE 8
Model (A4) > Static Structural (A5) > Analysis Settings
Step-Specific "Step Controls"

Step	Step End Time

1	1. s
2	3097. s
3	12966 s

TABLE 9
Model (A4) > Static Structural (A5) > Analysis Settings
Step-Specific "Creep Controls"

Step	Creep Effects	Creep Limit Ratio
1	Off	
2	On	100.
3	On	100.

TABLE 10
Model (A4) > Static Structural (A5) > Analysis Settings
Step-Specific "Output Controls"

Step	Max Number of Result Sets
1	Program Controlled
2	1000.
3	

TABLE 11
Model (A4) > Static Structural (A5) > Loads

Object Name	*Pressure*	*Fixed Support*	*Thermal Condition*
State	Fully Defined		
Scope			
Scoping Method	Geometry Selection		
Geometry	1 Face		1 Body
Definition			
Type	Pressure	Fixed Support	Thermal Condition
Define By	Normal To		
Magnitude	Tabular Data		Tabular Data

Suppressed	No		
Tabular Data			
Independent Variable	Time		Time

FIGURE 1
Model (A4) > Static Structural (A5) > Pressure

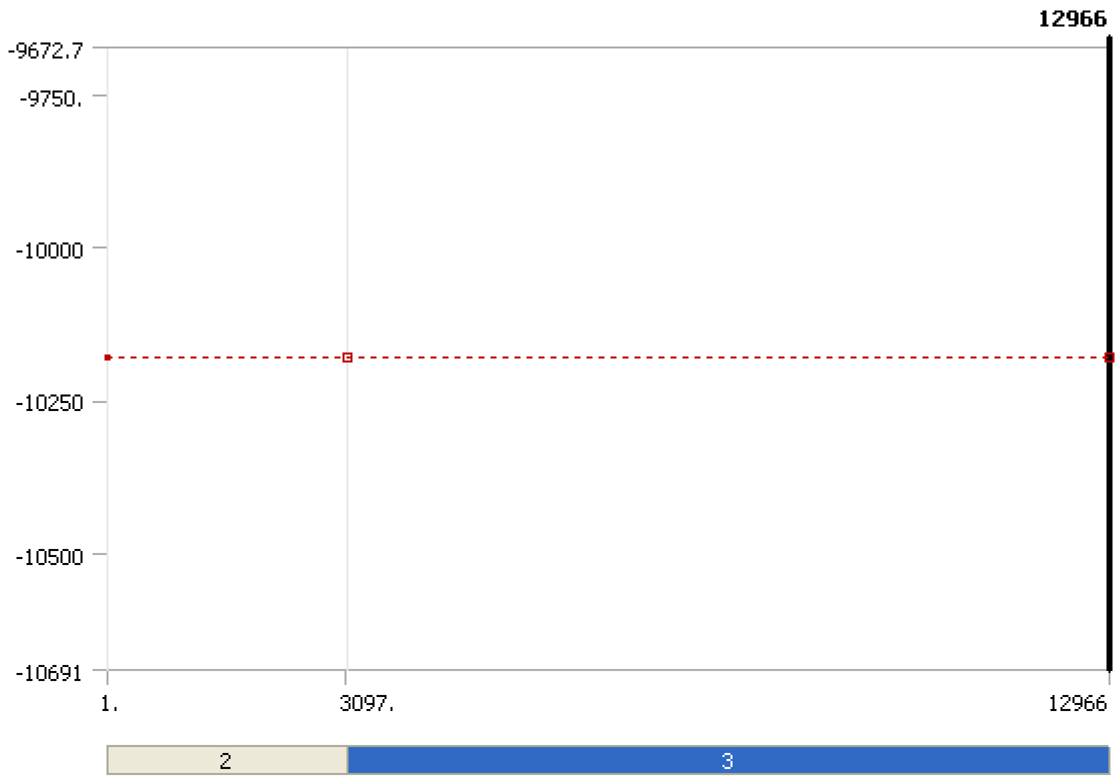


TABLE 12
Model (A4) > Static Structural (A5) > Pressure

Steps	Time [s]	Pressure [psi]
1	0.	-10182
	1.	
2	3097.	= -10182
3	12966	

FIGURE 2
Model (A4) > Static Structural (A5) > Thermal Condition

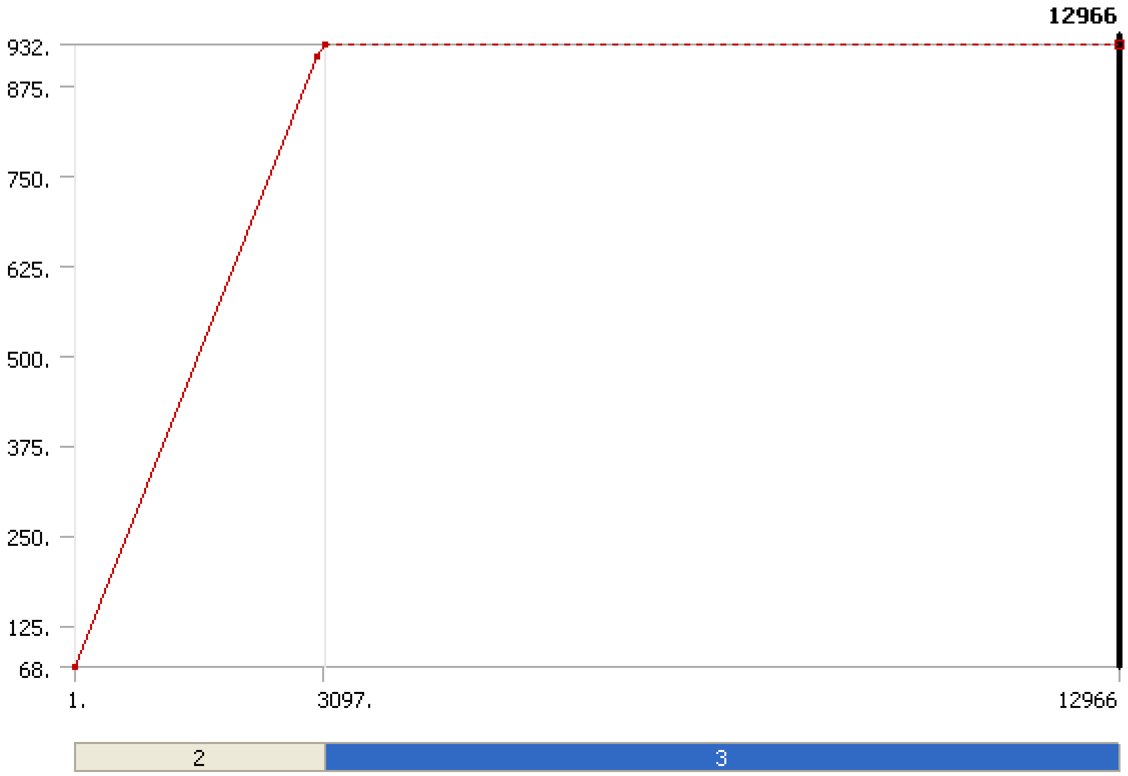


TABLE 13
Model (A4) > Static Structural (A5) > Thermal Condition

Steps	Time [s]	Temperature [°F]
1	0.	68.
	1.	
2	3000.	915.8
	3097.	932.
3	12966	= 932.

Solution (A6)

TABLE 14
Model (A4) > Static Structural (A5) > Solution

Object Name	*Solution (A6)*
State	Solved
Adaptive Mesh Refinement	
Max Refinement Loops	1.

Refinement Depth	2.
Information	
Status	Done

TABLE 15
Model (A4) > Static Structural (A5) > Solution (A6) > Solution Information

Object Name	*Solution Information*
State	Solved
Solution Information	
Solution Output	Solver Output
Newton-Raphson Residuals	0
Update Interval	2.5 s
Display Points	All
FE Connection Visibility	
Activate Visibility	Yes
Display	All FE Connectors
Draw Connections Attached To	All Nodes
Line Color	Connection Type
Visible on Results	No
Line Thickness	Single
Display Type	Lines

TABLE 16
Model (A4) > Static Structural (A5) > Solution (A6) > Results

Object Name	*Equivalent Plastic Strain*	*Total Deformation*	*Equivalent Creep Strain*
State	Solved		
Scope			
Scoping Method	Geometry Selection		

Geometry	All Bodies		
Definition			
Type	Equivalent Plastic Strain	Total Deformation	Equivalent Creep Strain
By	Time		
Display Time	Last		
Calculate Time History	Yes		
Identifier			
Suppressed	No		
Integration Point Results			
Display Option	Averaged		Averaged
Results			
Minimum	0. in/in	0. in	1.4206e-002 in/in
Maximum	0. in/in	7.3446e-002 in	2.1439e-002 in/in
Minimum Value Over Time			
Minimum	0. in/in	0. in	0. in/in
Maximum	0. in/in	0. in	1.4206e-002 in/in
Maximum Value Over Time			
Minimum	0. in/in	8.7451e-004 in	0. in/in
Maximum	0. in/in	7.3446e-002 in	2.1439e-002 in/in
Information			
Time	12966 s		
Load Step	3		
Substep	4		
Iteration Number	69		

FIGURE 3
Model (A4) > Static Structural (A5) > Solution (A6) > Equivalent Plastic Strain

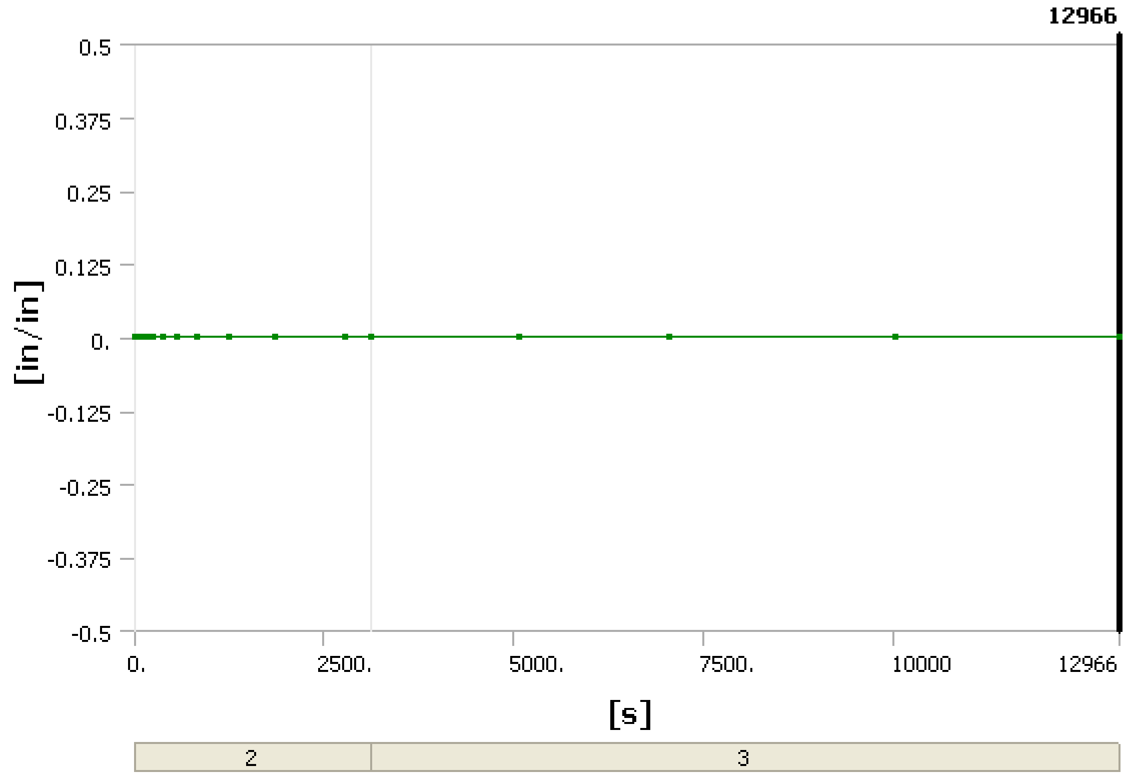


TABLE 17
Model (A4) > Static Structural (A5) > Solution (A6) > Equivalent Plastic Strain

<table>
<tr><th>Time [s]</th><th>Minimum [in/in]</th><th>Maximum [in/in]</th></tr>
<tr><td>0.2</td><td rowspan="11">0.</td><td rowspan="11">0.</td></tr>
<tr><td>0.4</td></tr>
<tr><td>0.7</td></tr>
<tr><td>1.</td></tr>
<tr><td>5.8165</td></tr>
<tr><td>10.633</td></tr>
<tr><td>15.45</td></tr>
<tr><td>22.567</td></tr>
<tr><td>33.244</td></tr>
<tr><td>49.259</td></tr>
<tr><td>73.281</td></tr>
</table>

109.32		
163.37		
244.44		
366.06		
548.48		
822.11		
1232.6		
1848.2		
2771.7		
3097.		
5070.8		
7044.6		
10005		
12966		

FIGURE 4
Model (A4) > Static Structural (A5) > Solution (A6) > Total Deformation

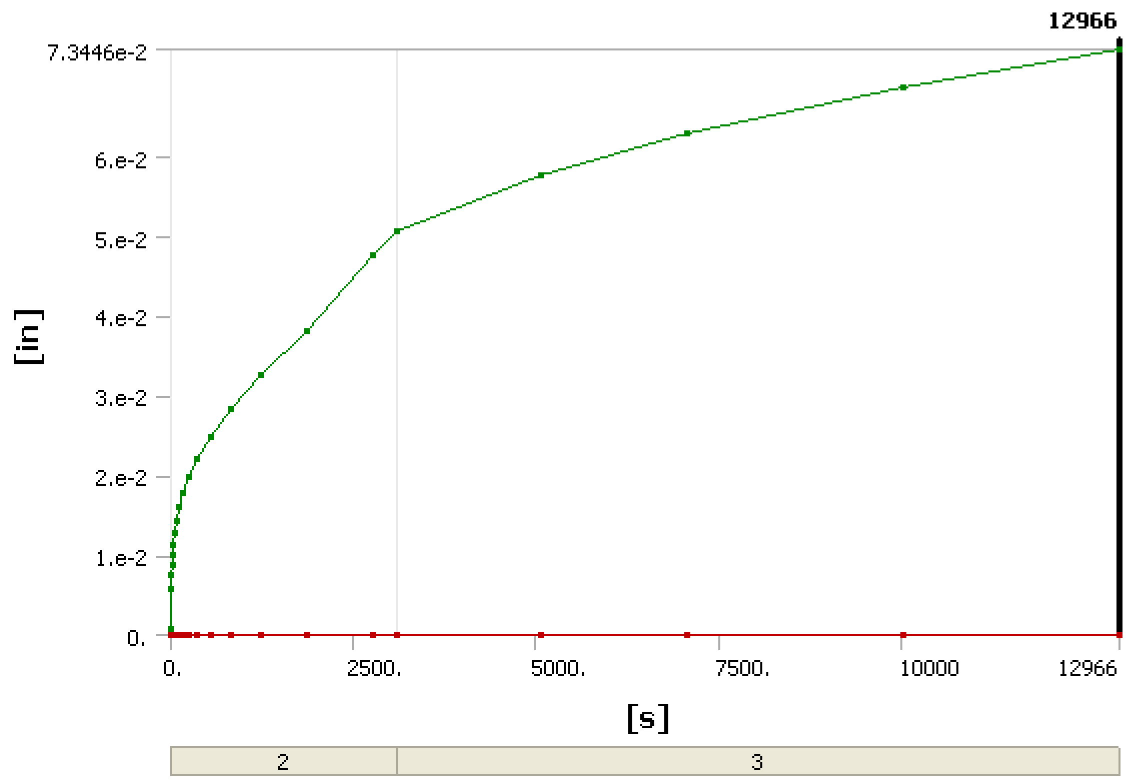


TABLE 18
Model (A4) > Static Structural (A5) > Solution (A6) > Total Deformation

Time [s]	Minimum [in]	Maximum [in]
0.2		
0.4		8.7451e-004
0.7		
1.		
5.8165		5.7559e-003
10.633	0.	7.591e-003
15.45		8.7779e-003
22.567		1.0027e-002
33.244		1.136e-002
49.259		1.2781e-002
73.281		1.4304e-002

109.32		1.5951e-002
163.37		1.7759e-002
244.44		1.9783e-002
366.06		2.2104e-002
548.48		2.4849e-002
822.11		2.8223e-002
1232.6		3.2474e-002
1848.2		3.8003e-002
2771.7		4.7556e-002
3097.		5.0648e-002
5070.8		5.7726e-002
7044.6		6.2869e-002
10005		6.8778e-002
12966		7.3446e-002

FIGURE 5
Model (A4) > Static Structural (A5) > Solution (A6) > Equivalent Creep Strain

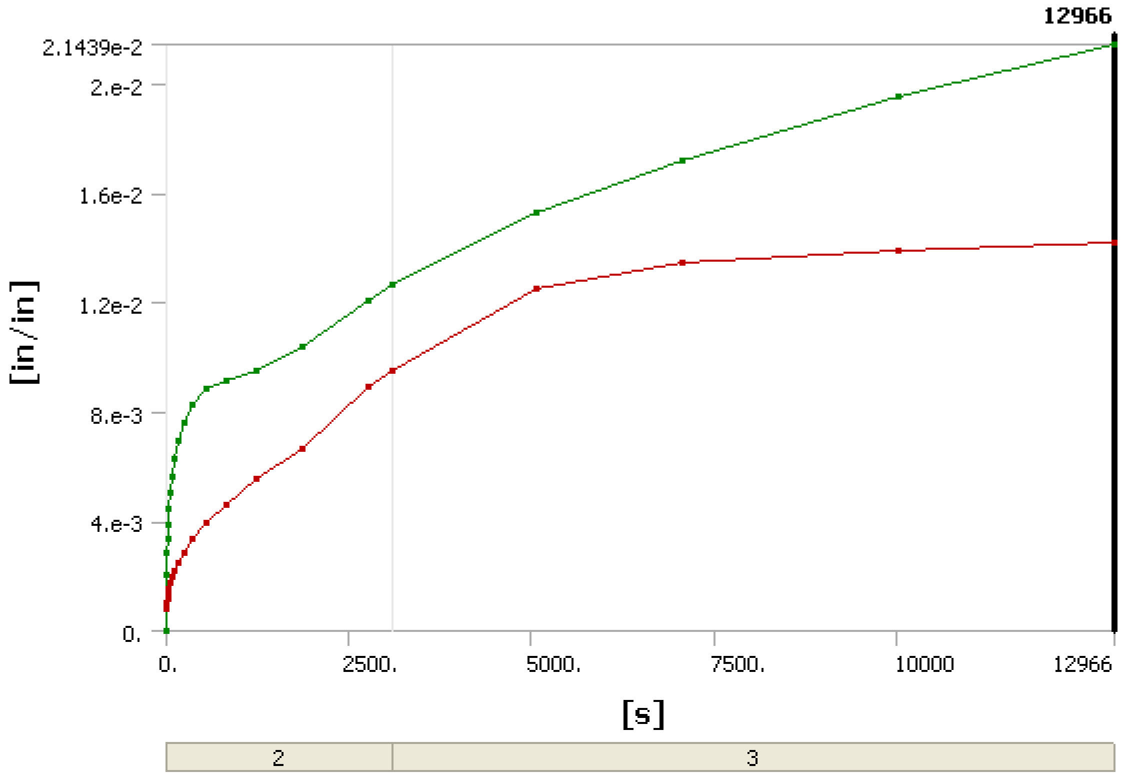


TABLE 19
Model (A4) > Static Structural (A5) > Solution (A6) > Equivalent Creep Strain

Time [s]	Minimum [in/in]	Maximum [in/in]
0.2	0.	0.
0.4		
0.7		
1.		
5.8165	8.0971e-004	2.0722e-003
10.633	1.0473e-003	2.8573e-003
15.45	1.1965e-003	3.3644e-003
22.567	1.3549e-003	3.8956e-003
33.244	1.5291e-003	4.4562e-003
49.259	1.7239e-003	5.0432e-003
73.281	1.9459e-003	5.6543e-003

109.32	2.2047e-003	6.2875e-003
163.37	2.5127e-003	6.9393e-003
244.44	2.8864e-003	7.6024e-003
366.06	3.3469e-003	8.2562e-003
548.48	3.9212e-003	8.8362e-003
822.11	4.6417e-003	9.1742e-003
1232.6	5.5421e-003	9.5391e-003
1848.2	6.6507e-003	1.0375e-002
2771.7	8.9156e-003	1.2085e-002
3097.	9.5274e-003	1.2683e-002
5070.8	1.249e-002	1.526e-002
7044.6	1.3472e-002	1.7183e-002
10005	1.3917e-002	1.9553e-002
12966	1.4206e-002	2.1439e-002

Material Data

Structural Steel

TABLE 20
Structural Steel > Constants

Density	0.2836 lbm in^-3
Coefficient of Thermal Expansion	6.6667e-006 F^-1
Specific Heat	0.10366 BTU lbm^-1 F^-1
Thermal Conductivity	8.0917e-004 BTU s^-1 in^-1 F^-1
Resistivity	8.5235 ohm cmil in^-1

TABLE 21
Structural Steel > Compressive Ultimate Strength

Compressive Ultimate Strength psi

0

TABLE 22
Structural Steel > Compressive Yield Strength

Compressive Yield Strength psi
36259

TABLE 23
Structural Steel > Tensile Yield Strength

Tensile Yield Strength psi
36259

TABLE 24
Structural Steel > Tensile Ultimate Strength

Tensile Ultimate Strength psi
66717

TABLE 25
Structural Steel > Isotropic Secant Coefficient of Thermal Expansion

Reference Temperature F
71.6

TABLE 26
Structural Steel > Alternating Stress Mean Stress

Alternating Stress psi	Cycles	Mean Stress psi
5.8001e+005	10	0
4.1002e+005	20	0
2.7499e+005	50	0
2.0494e+005	100	0
1.5505e+005	200	0
63962	2000	0
38000	10000	0
31038	20000	0

20015	1.e+005	0
16534	2.e+005	0
12502	1.e+006	0

TABLE 27
Structural Steel > Strain-Life Parameters

Strength Coefficient psi	Strength Exponent	Ductility Coefficient	Ductility Exponent	Cyclic Strength Coefficient psi	Cyclic Strain Hardening Exponent
1.3343e+005	-0.106	0.213	-0.47	1.4504e+005	0.2

TABLE 28
Structural Steel > Isotropic Elasticity

Temperature F	Young's Modulus psi	Poisson's Ratio	Bulk Modulus psi	Shear Modulus psi
71.6	2.9008e+007	0.3	2.4173e+007	1.1157e+007
212	2.9008e+007	0.3	2.4173e+007	1.1157e+007
392	2.6107e+007	0.3	2.1756e+007	1.0041e+007
572	2.3206e+007	0.3	1.9338e+007	8.9254e+006
752	2.0305e+007	0.3	1.6921e+007	7.8097e+006
932	1.7405e+007	0.3	1.4504e+007	6.694e+006
1112	8.9778e+006	0.3	7.4815e+006	3.453e+006
1292	3.771e+006	0.3	3.1425e+006	1.4504e+006
1472	2.6107e+006	0.3	2.1756e+006	1.0041e+006
1652	1.96e-004	0.3	1.6333e-004	7.5385e-005

TABLE 29
Structural Steel > Isotropic Relative Permeability

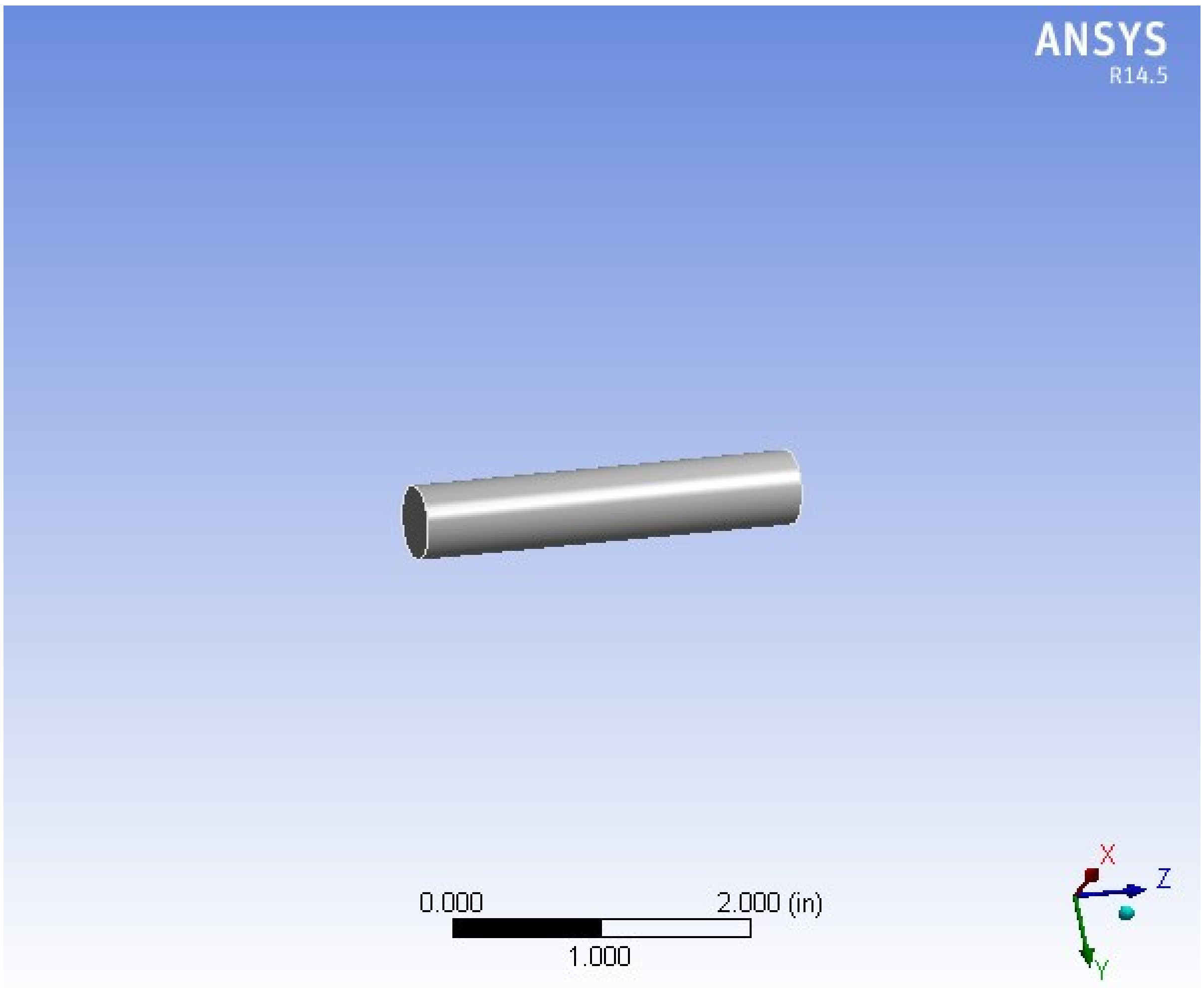
Relative Permeability
10000

TABLE 30
Structural Steel > Modified Time Hardening

Temperature F	Creep Constant 1	Creep Constant 2	Creep Constant 3	Creep Constant 4
842	1.99e-004	0.22242	-0.92865	246.51
932	3.27e-007	0.8548	-0.77998	2.3651
1022	2.41e-007	0.82136	-0.51722	9.461

Third Model (550^o C)

Product Version	14.5.7 Release



Contents

Units

TABLE 1

Unit System	U.S. Customary (in, lbm, lbf, s, V, A) Degrees rad/s Fahrenheit
Angle	Degrees
Rotational Velocity	rad/s
Temperature	Fahrenheit

Model (A4)

Geometry

TABLE 2
Model (A4) > Geometry

Object Name	*Geometry*
State	Fully Defined
Definition	
Type	DesignModeler
Length Unit	Inches
Element Control	Program Controlled
Display Style	Body Color

Bounding Box	
Length X	0.5 in
Length Y	0.5 in
Length Z	2.69 in
Properties	
Volume	0.52818 in³
Mass	0.14979 lbm
Scale Factor Value	1.
Statistics	
Bodies	1
Active Bodies	1
Nodes	12955
Elements	2800
Mesh Metric	None
Basic Geometry Options	
Parameters	Yes
Parameter Key	DS
Attributes	No
Named Selections	No
Material Properties	No
Advanced Geometry Options	
Use Associativity	Yes
Coordinate Systems	No
Reader Mode Saves Updated File	No
Use Instances	Yes

Smart CAD Update	No
Attach File Via Temp File	Yes
Analysis Type	3-D
Decompose Disjoint Geometry	Yes
Enclosure and Symmetry Processing	Yes

TABLE 3
Model (A4) > Geometry > Parts

Object Name	*Solid*
State	Meshed
Graphics Properties	
Visible	Yes
Transparency	1
Definition	
Suppressed	No
Stiffness Behavior	Flexible
Coordinate System	Default Coordinate System
Reference Temperature	By Environment
Material	
Assignment	Structural Steel
Nonlinear Effects	Yes
Thermal Strain Effects	Yes
Bounding Box	
Length X	0.5 in
Length Y	0.5 in
Length Z	2.69 in
Properties	

Volume	0.52818 in³
Mass	0.14979 lbm
Centroid X	5.2267e-018 in
Centroid Y	1.9256e-018 in
Centroid Z	1.345 in
Moment of Inertia Ip1	9.2184e-002 lbm·in²
Moment of Inertia Ip2	9.2184e-002 lbm·in²
Moment of Inertia Ip3	4.6337e-003 lbm·in²
Statistics	
Nodes	12955
Elements	2800
Mesh Metric	None

Coordinate Systems

TABLE 4
Model (A4) > Coordinate Systems > Coordinate System

Object Name	*Global Coordinate System*
State	Fully Defined
Definition	
Type	Cartesian
Coordinate System ID	0.
Origin	
Origin X	0. in
Origin Y	0. in
Origin Z	0. in
Directional Vectors	
X Axis Data	[1. 0. 0.]

Y Axis Data	[0. 1. 0.]
Z Axis Data	[0. 0. 1.]

Mesh

TABLE 5
Model (A4) > Mesh

Object Name	*Mesh*
State	Solved
Defaults	
Physics Preference	Mechanical
Relevance	0
Sizing	
Use Advanced Size Function	Off
Relevance Center	Medium
Element Size	Default
Initial Size Seed	Active Assembly
Smoothing	Medium
Transition	Fast
Span Angle Center	Coarse
Minimum Edge Length	1.57080 in
Inflation	
Use Automatic Inflation	None
Inflation Option	Smooth Transition
Transition Ratio	0.272
Maximum Layers	5
Growth Rate	1.2
Inflation Algorithm	Pre

View Advanced Options	No
Patch Conforming Options	
Triangle Surface Mesher	Program Controlled
Advanced	
Shape Checking	Standard Mechanical
Element Midside Nodes	Program Controlled
Straight Sided Elements	No
Number of Retries	Default (4)
Extra Retries For Assembly	Yes
Rigid Body Behavior	Dimensionally Reduced
Mesh Morphing	Disabled
Defeaturing	
Pinch Tolerance	Please Define
Generate Pinch on Refresh	No
Automatic Mesh Based Defeaturing	On
Defeaturing Tolerance	Default
Statistics	
Nodes	12955
Elements	2800
Mesh Metric	None

Static Structural (A5)

TABLE 6
Model (A4) > Analysis

Object Name	*Static Structural (A5)*
State	Solved
Definition	

Physics Type	Structural
Analysis Type	Static Structural
Solver Target	Mechanical APDL
Options	
Environment Temperature	71.6 °F
Generate Input Only	No

TABLE 7
Model (A4) > Static Structural (A5) > Analysis Settings

Object Name	*Analysis Settings*
State	Fully Defined
Step Controls	
Number Of Steps	3.
Current Step Number	3.
Step End Time	10662 s
Auto Time Stepping	Program Controlled
Solver Controls	
Solver Type	Program Controlled
Weak Springs	Program Controlled
Large Deflection	Off
Inertia Relief	Off
Restart Controls	
Generate Restart Points	Program Controlled
Retain Files After Full Solve	No
Creep Controls	
Creep Effects	On
Nonlinear Controls	

Force Convergence	Program Controlled
Moment Convergence	Program Controlled
Displacement Convergence	Program Controlled
Rotation Convergence	Program Controlled
Line Search	Program Controlled
Stabilization	Off
Output Controls	
Stress	Yes
Strain	Yes
Nodal Forces	No
Contact Miscellaneous	No
General Miscellaneous	No
Store Results At	All Time Points
Max Number of Result Sets	1000.
Analysis Data Management	
Future Analysis	None
Scratch Solver Files Directory	
Save MAPDL db	No
Delete Unneeded Files	Yes
Nonlinear Solution	Yes
Solver Units	Active System
Solver Unit System	Bin

TABLE 8
Model (A4) > Static Structural (A5) > Analysis Settings
Step-Specific "Step Controls"

Step	Step End Time

1	1. s
2	3670. s
3	10662 s

TABLE 9
Model (A4) > Static Structural (A5) > Analysis Settings
Step-Specific "Creep Controls"

Step	Creep Effects	Creep Limit Ratio
1	Off	
2	On	100.
3	On	100.

TABLE 10
Model (A4) > Static Structural (A5) > Analysis Settings
Step-Specific "Output Controls"

Step	Max Number of Result Sets
1	Program Controlled
2	1000.
3	

TABLE 11
Model (A4) > Static Structural (A5) > Loads

Object Name	*Pressure*	*Fixed Support*	*Thermal Condition*
State	Fully Defined		
Scope			
Scoping Method	Geometry Selection		
Geometry	1 Face		1 Body
Definition			
Type	Pressure	Fixed Support	Thermal Condition
Define By	Normal To		
Magnitude	Tabular Data		Tabular Data

Suppressed	No		
Tabular Data			
Independent Variable	Time		Time

FIGURE 1
Model (A4) > Static Structural (A5) > Pressure

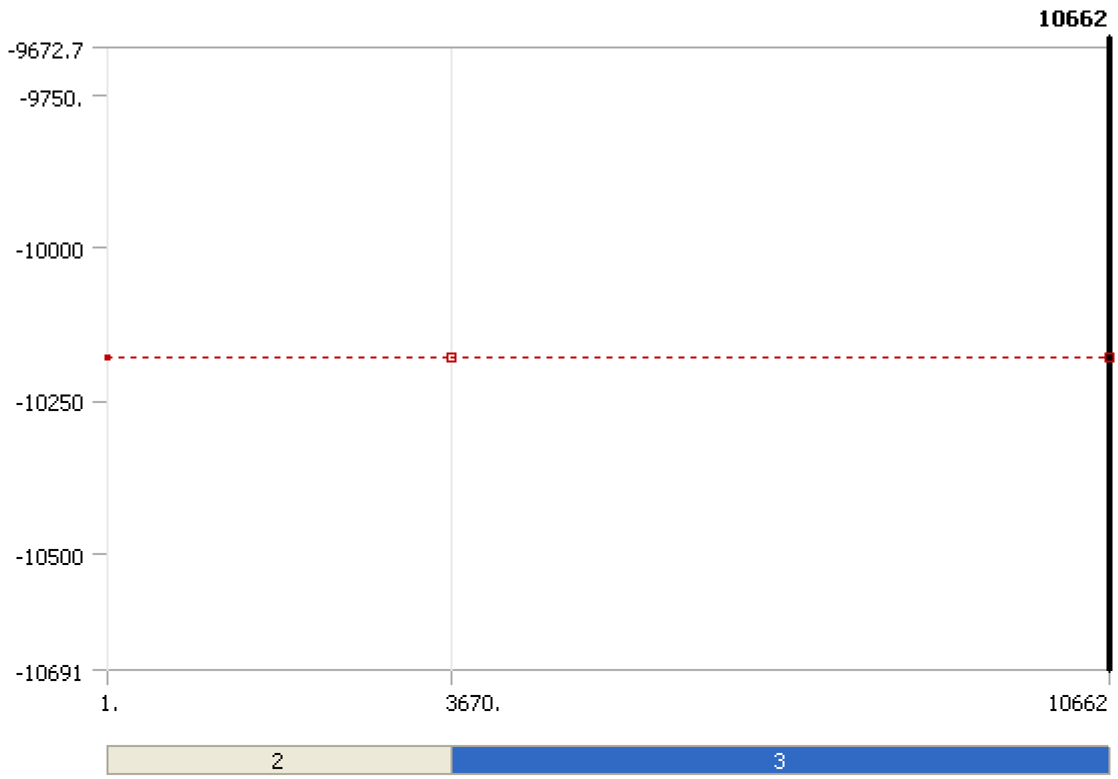


TABLE 12
Model (A4) > Static Structural (A5) > Pressure

Steps	Time [s]	Pressure [psi]
1	0.	-10182
	1.	
2	3670.	= -10182
3	10662	

FIGURE 2
Model (A4) > Static Structural (A5) > Thermal Condition

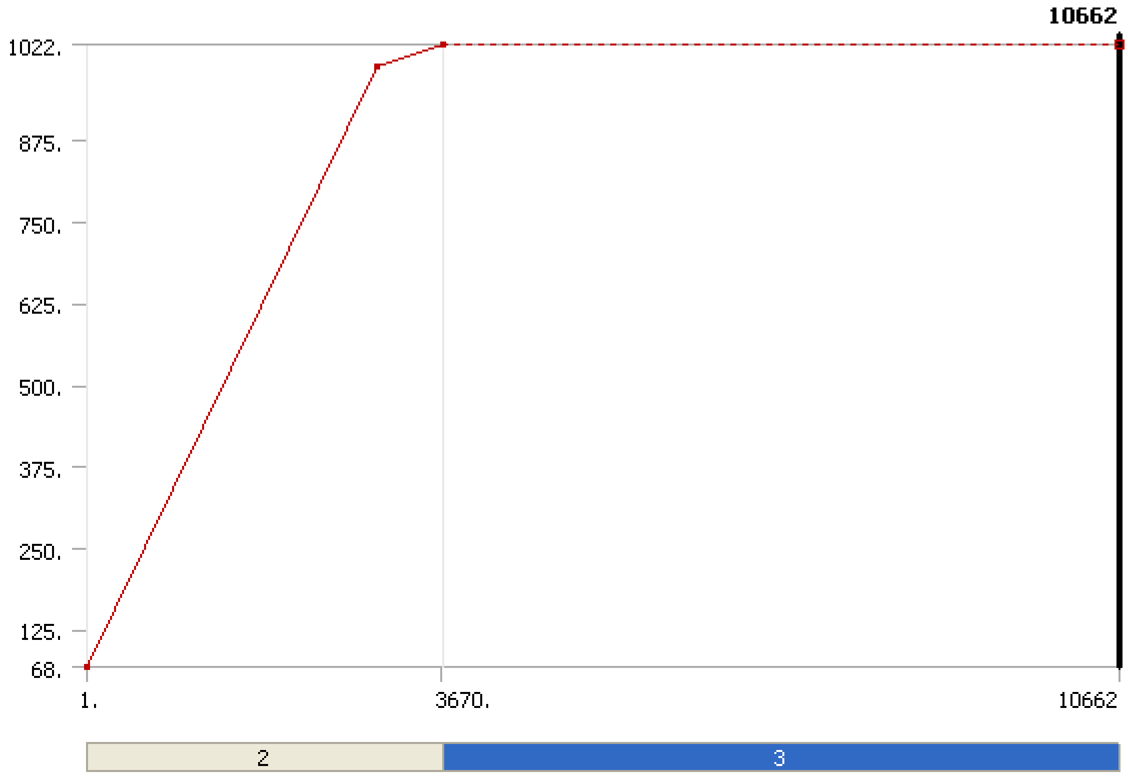


TABLE 13
Model (A4) > Static Structural (A5) > Thermal Condition

Steps	Time [s]	Temperature [°F]
1	0.	68.
	1.	
2	3000.	989.6
	3670.	1022.
3	10662	= 1022.

Solution (A6)

TABLE 14
Model (A4) > Static Structural (A5) > Solution

Object Name	*Solution (A6)*
State	Solved
Adaptive Mesh Refinement	
Max Refinement Loops	1.

Refinement Depth	2.
Information	
Status	Done

TABLE 15
Model (A4) > Static Structural (A5) > Solution (A6) > Solution Information

Object Name	*Solution Information*
State	Solved
Solution Information	
Solution Output	Solver Output
Newton-Raphson Residuals	0
Update Interval	2.5 s
Display Points	All
FE Connection Visibility	
Activate Visibility	Yes
Display	All FE Connectors
Draw Connections Attached To	All Nodes
Line Color	Connection Type
Visible on Results	No
Line Thickness	Single
Display Type	Lines

TABLE 16
Model (A4) > Static Structural (A5) > Solution (A6) > Results

Object Name	*Equivalent Plastic Strain*	*Total Deformation*	*Equivalent Creep Strain*
State	Solved		
Scope			
Scoping Method	Geometry Selection		

Geometry	All Bodies		
Definition			
Type	Equivalent Plastic Strain	Total Deformation	Equivalent Creep Strain
By	Time		
Display Time	Last		
Calculate Time History	Yes		
Identifier			
Suppressed	No		
Integration Point Results			
Display Option	Averaged		Averaged
Results			
Minimum	0. in/in	0. in	2.0159e-002 in/in
Maximum	0. in/in	0.16367 in	6.0362e-002 in/in
Minimum Value Over Time			
Minimum	0. in/in	0. in	0. in/in
Maximum	0. in/in	0. in	2.0159e-002 in/in
Maximum Value Over Time			
Minimum	0. in/in	8.7451e-004 in	0. in/in
Maximum	0. in/in	0.16367 in	6.0362e-002 in/in
Information			
Time	10662 s		
Load Step	3		
Substep	4		
Iteration Number	73		

FIGURE 3
Model (A4) > Static Structural (A5) > Solution (A6) > Equivalent Plastic Strain

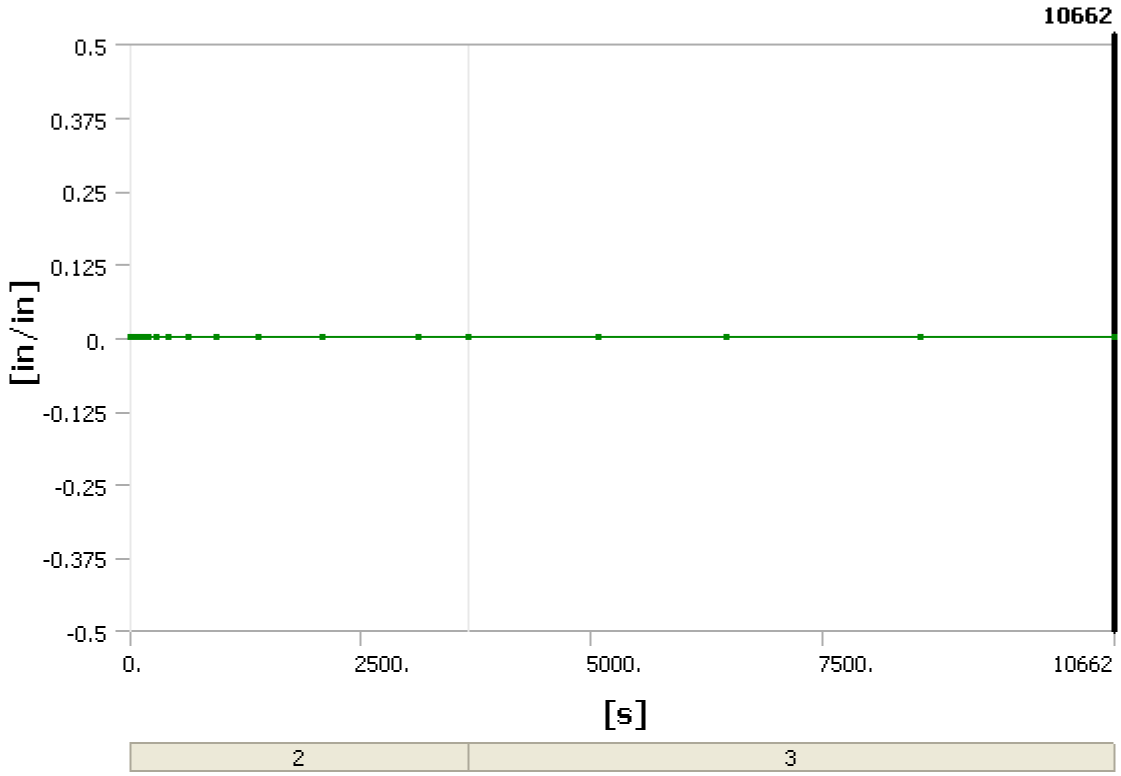


TABLE 17
Model (A4) > Static Structural (A5) > Solution (A6) > Equivalent Plastic Strain

Time [s]	Minimum [in/in]	Maximum [in/in]
0.2		
0.4		
0.7		
1.		
4.669		
8.338	0.	0.
12.007		
17.46		
25.491		
37.538		
55.609		

82.714		
123.37		
184.36		
275.84		
413.06		
618.89		
927.64		
1390.8		
2085.5		
3127.5		
3670.		
5068.4		
6466.8		
8564.4		
10662		

FIGURE 4
Model (A4) > Static Structural (A5) > Solution (A6) > Total Deformation

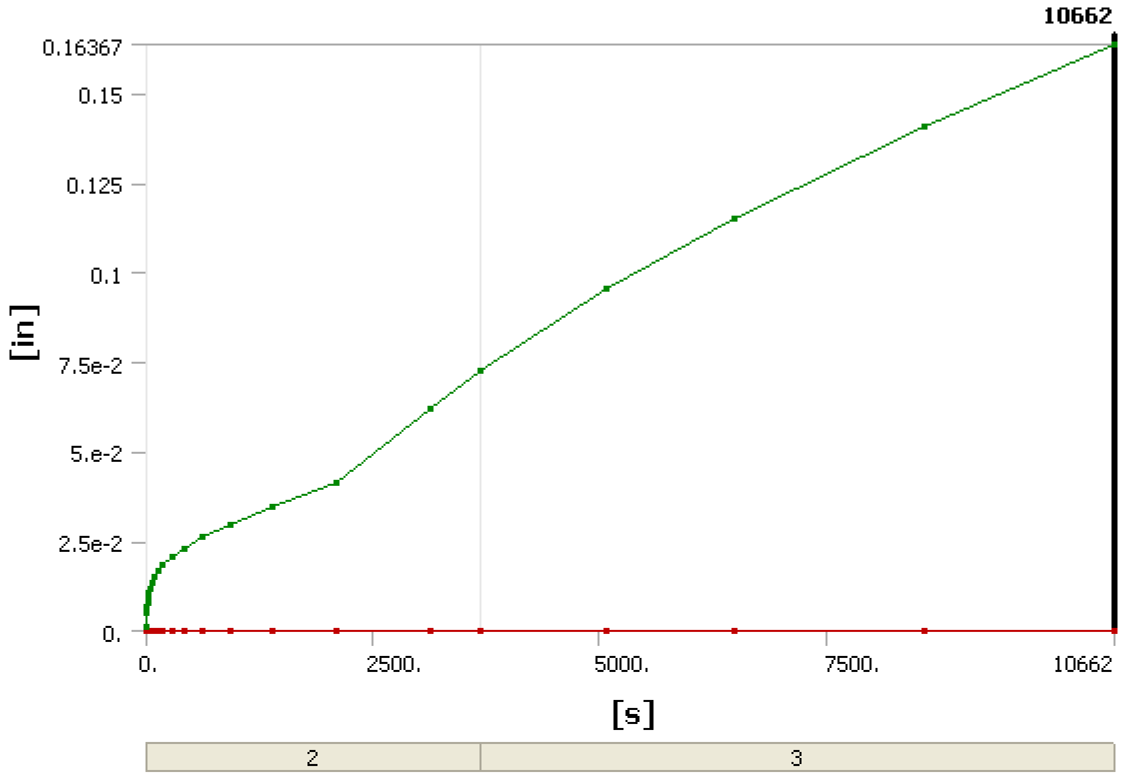


TABLE 18
Model (A4) > Static Structural (A5) > Solution (A6) > Total Deformation

Time [s]	Minimum [in]	Maximum [in]
0.2	0.	8.7451e-004
0.4		
0.7		
1.		
4.669		5.1115e-003
8.338		6.843e-003
12.007		7.9773e-003
17.46		9.1835e-003
25.491		1.0452e-002
37.538		1.1809e-002
55.609		1.3263e-002

82.714		1.4831e-002
123.37		1.6541e-002
184.36		1.8438e-002
275.84		2.0587e-002
413.06		2.309e-002
618.89		2.6114e-002
927.64		2.9877e-002
1390.8		3.4697e-002
2085.5		4.1071e-002
3127.5		6.1768e-002
3670.		7.2504e-002
5068.4		9.5338e-002
6466.8		0.11509
8564.4		0.14093
10662		0.16367

FIGURE 5
Model (A4) > Static Structural (A5) > Solution (A6) > Equivalent Creep Strain

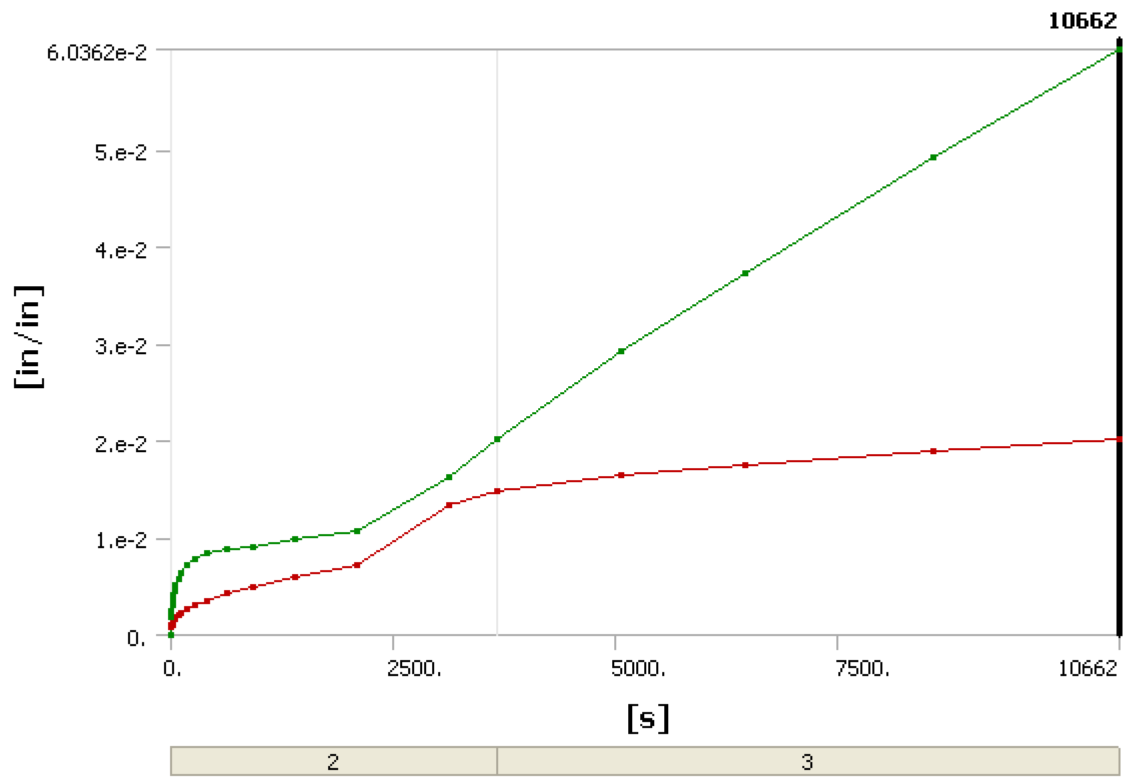


TABLE 19
Model (A4) > Static Structural (A5) > Solution (A6) > Equivalent Creep Strain

Time [s]	Minimum [in/in]	Maximum [in/in]
0.2	0.	0.
0.4		
0.7		
1.		
4.669	7.4757e-004	1.7908e-003
8.338	9.7123e-004	2.5304e-003
12.007	1.1128e-003	3.0152e-003
17.46	1.2641e-003	3.5293e-003
25.491	1.4271e-003	4.0656e-003
37.538	1.6086e-003	4.6314e-003
55.609	1.8142e-003	5.2237e-003

82.714	2.0517e-003	5.84e-003
123.37	2.3318e-003	6.4775e-003
184.36	2.669e-003	7.1311e-003
275.84	3.0816e-003	7.7885e-003
413.06	3.5935e-003	8.4134e-003
618.89	4.2347e-003	8.8929e-003
927.64	5.0383e-003	9.0474e-003
1390.8	6.0364e-003	9.8107e-003
2085.5	7.2495e-003	1.0675e-002
3127.5	1.3319e-002	1.6215e-002
3670.	1.4909e-002	2.0093e-002
5068.4	1.6432e-002	2.9277e-002
6466.8	1.7548e-002	3.7235e-002
8564.4	1.8946e-002	4.9326e-002
10662	2.0159e-002	6.0362e-002

Material Data

Structural Steel

TABLE 20
Structural Steel > Constants

Density	0.2836 lbm in^-3
Coefficient of Thermal Expansion	6.6667e-006 F^-1
Specific Heat	0.10366 BTU lbm^-1 F^-1
Thermal Conductivity	8.0917e-004 BTU s^-1 in^-1 F^-1
Resistivity	8.5235 ohm cmil in^-1

TABLE 21
Structural Steel > Compressive Ultimate Strength

Compressive Ultimate Strength psi
0

TABLE 22
Structural Steel > Compressive Yield Strength

Compressive Yield Strength psi
36259

TABLE 23
Structural Steel > Tensile Yield Strength

Tensile Yield Strength psi
36259

TABLE 24
Structural Steel > Tensile Ultimate Strength

Tensile Ultimate Strength psi
66717

TABLE 25
Structural Steel > Isotropic Secant Coefficient of Thermal Expansion

Reference Temperature F
71.6

TABLE 26
Structural Steel > Alternating Stress Mean Stress

Alternating Stress psi	Cycles	Mean Stress psi
5.8001e+005	10	0
4.1002e+005	20	0
2.7499e+005	50	0
2.0494e+005	100	0
1.5505e+005	200	0
63962	2000	0
38000	10000	0

31038	20000	0
20015	1.e+005	0
16534	2.e+005	0
12502	1.e+006	0

TABLE 27
Structural Steel > Strain-Life Parameters

Strength Coefficient psi	Strength Exponent	Ductility Coefficient	Ductility Exponent	Cyclic Strength Coefficient psi	Cyclic Strain Hardening Exponent
1.3343e+005	-0.106	0.213	-0.47	1.4504e+005	0.2

TABLE 28
Structural Steel > Isotropic Elasticity

Temperature F	Young's Modulus psi	Poisson's Ratio	Bulk Modulus psi	Shear Modulus psi
71.6	2.9008e+007	0.3	2.4173e+007	1.1157e+007
212	2.9008e+007	0.3	2.4173e+007	1.1157e+007
392	2.6107e+007	0.3	2.1756e+007	1.0041e+007
572	2.3206e+007	0.3	1.9338e+007	8.9254e+006
752	2.0305e+007	0.3	1.6921e+007	7.8097e+006
932	1.7405e+007	0.3	1.4504e+007	6.694e+006
1112	8.99e+006	0.3	7.4917e+006	3.4577e+006
1292	3.771e+006	0.3	3.1425e+006	1.4504e+006
1472	2.6107e+006	0.3	2.1756e+006	1.0041e+006
1652	1.96e+006	0.3	1.6334e+006	7.5386e+005

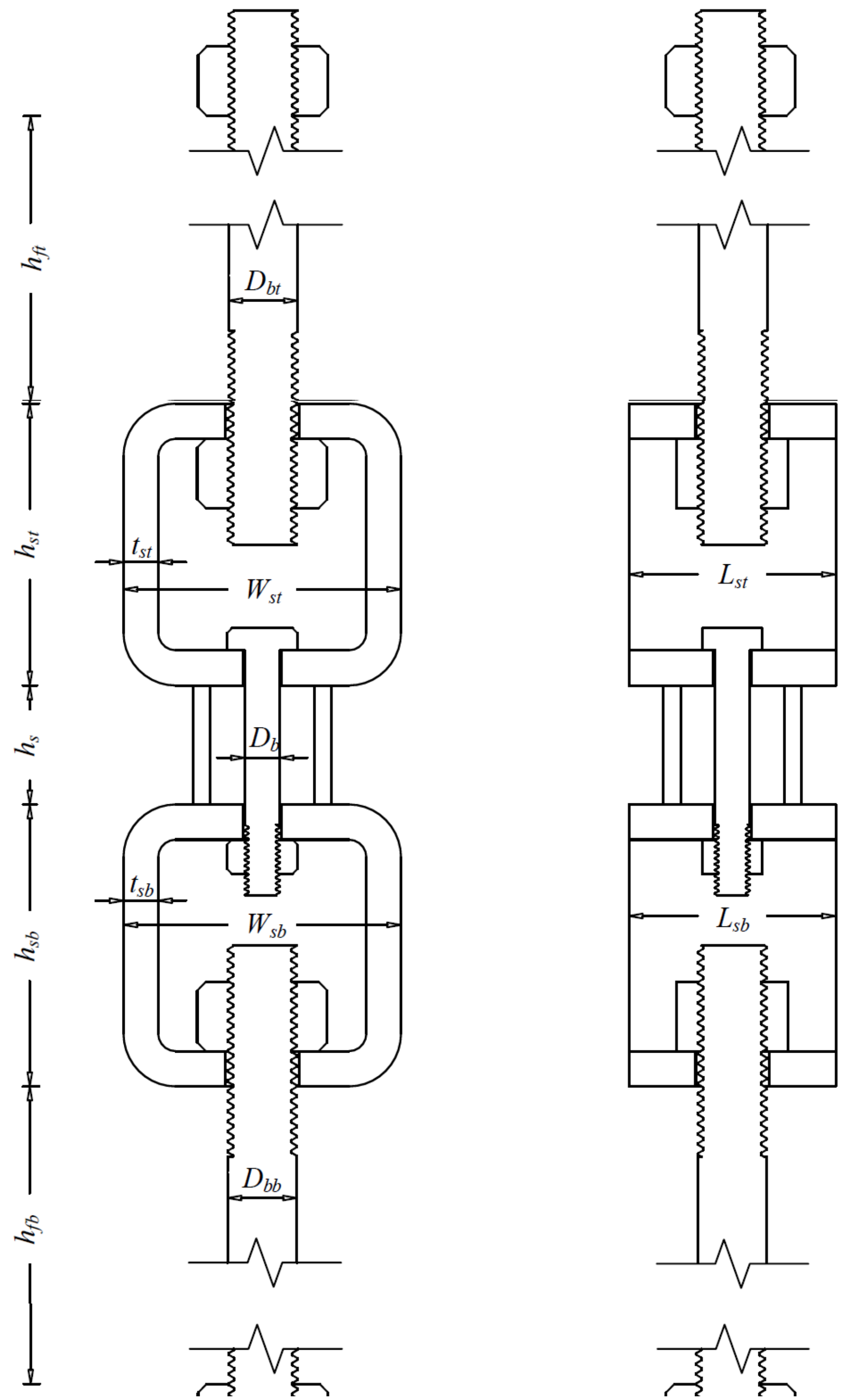
TABLE 29
Structural Steel > Isotropic Relative Permeability

Relative Permeability
10000

TABLE 30
Structural Steel > Modified Time Hardening

Temperature F	Creep Constant 1	Creep Constant 2	Creep Constant 3	Creep Constant 4
842	1.99e-004	0.22242	-0.92865	246.51
932	3.27e-007	0.8548	-0.77998	2.3651
1022	2.41e-007	0.82136	-0.51722	9.461

Dimensions of Setup Fixtures



Symbol	Description	Value (in)
h_{ft}	Distance from the top fixed end to the top hollow square section	19.44
h_{fb}	Distance from the bottom fixed end to the bottom hollow square section	17.75
h_s	Height of the spacer piece	1.69
D_{bt}	Diameter of the top vertical bar	1
D_{bb}	Diameter of the bottom vertical bar	1
D_b	Diameter of the bolt	0.5
h_{st}	Height of the top hollow square section	4
h_{sb}	Height of the bottom hollow square section	4
W_{st}	Width of the top hollow square section	4
W_{sb}	Width of the bottom hollow square section	4
L_{st}	Length of the top hollow square section	3
L_{sb}	Length of the bottom hollow square section	3
t_{st}	Thickness of the top hollow square section	0.5
t_{sb}	Thickness of the bottom hollow square section	0.5